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TNO report

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Techno-economic uptake potential of zero-emission trucks in Europe

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Summary

Zero-emission vehicles (ZEVs) are widely regarded as an effective way to reduce CO_2 emissions and decarbonise the heavy-duty vehicle (HDV) sector. However, the speed at which the transition from internal combustion engine vehicles (ICEVs) towards battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) will happen and for which vehicle segments is still uncertain.

Key drivers which will determine the market uptake include the expected technology improvements and cost reductions of vehicle components such as batteries, fuel cells and hydrogen storage tanks as well as the future development of energy prices including diesel, electricity and renewable hydrogen. Possible constraints such as insufficient vehicle ranges, insufficient availability of charging / fuelling infrastructure, additional downtime due to longer charging and refuelling times or payload losses due to heavier vehicles could potentially delay the market uptake.

This report assesses the techno-economic feasibility and market uptake potential of zero-emission trucks for the European Union (EU) and the United Kingdom (UK) over the timeframe 2020 – 2040. The analysis is carried out for four different vehicle segments, i.e. rigid trucks for urban delivery and three different articulated tractor-trailers for regional delivery, long haul and construction.

Switching from ICEVs to ZEVs is considered feasible in this analysis if TCO parity with diesel equivalents is reached (affordability) and operational limitations such as range constraints, time or payload losses can be avoided (applicability). To determine whether range limitations are barriers for the uptake of ZEVs for certain types of vehicle use, account was taken of the distribution of average daily mileages of the fleet as well as day-to-day distance variations of individual vehicles. Based on the expected affordability and applicability, the analysis forecasts the ZEV uptake potential for each vehicle segment until the year 2040. A subsequent analysis also examines an accelerated market uptake scenario where policy measures such as vehicle purchase subsidies, CO_2-based road tolls and CO_2 pricing of transport fuels are taken into account.

The actual uptake of ZEVs will likely differ from the uptake potential as determined in this study. This is due to the fact that besides the factors mentioned above that are taken into account (i.e. affordability and applicability) many other factors affect the actual uptake, such as the availability of charging and refuelling infrastructure, availability of vehicles and uncertainties over new technologies.

Based on the results of this report, BEVs are expected to be the most cost-effective option for all of the included vehicle types. This would even be the case if battery prices do not come down as fast as expected, diesel prices would be relatively low or electricity prices relatively high. However, due to range limitations, battery electric vehicles can potentially not be used for very long trips which make them unsuitable for replacing trucks with high average daily mileages or longer trips for part of the time. This however concerns only a limited number of the trucks.

FCEVs can be a zero-emission alternative for diesel trucks that drive very large distances at least part of the time. However, it is expected that these will not be cost competitive with diesel. Even at lower hydrogen prices or lower fuel cell costs, FCEVs only become the most cost-effective technology from 2030 onwards for a very limited share of the fleet and only in a small number of countries.

The estimated aggregated ZEV uptake potential for all urban, regional delivery and long haul trucks reaches 99.8% by 2035. For 0.2% of the fleet sales, ZEVs cannot replace diesel trucks due to range limitations (BEVs) or because they are not cost-competitive (FCEVs). For the construction trucks, a 100% ZEV uptake potential is reached in 2033. Despite the differences in vehicle range requirements and energy prices, the variation in ZEV uptake potential between the regions in Europe is found to be limited. The maximum difference between regions is approximately a three years delay and the final uptake potential is equal in all regions.

Based on the purchase subsidy schemes in seven different European countries, the uptake potential is advanced significantly during the early years but does not change much in the 2030s. Since the subsidies are only assumed to apply until 2024, the uptake potential beyond 2024 is not affected. The effect of CO_2-based tolling on the ZEV uptake potential is also significant up to 2030 as the uptake potential is brought forward by one to three years. CO_2 pricing (ETS2) leads to higher fuel costs for diesel trucks. As a result of the increased diesel price, the relative cost-competitiveness for zero-emission alternatives improves. Nevertheless, the impact on the ZEV uptake potential is negligible.

Although it is concluded that FCEVs are not the most cost-competitive drivetrain for any of the types of vehicles assessed, it does not mean that FCEVs will not play a role in the decarbonisation of the road freight sector. There may be other types of vehicles, such as vocational and special purpose vehicles that are out of scope of this study for which hydrogen may be the most cost-competitive option. But even for mainstream road freight applications some limited share of other solutions on the vehicle or logistics side may be required to meet the long term zero-CO_2 objective if the boundary conditions for the projected ZEV uptake are not met in time.

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Abbreviations & List of symbols

BEV	Battery electric vehicle
FCEV	Fuel cell electric vehicle
HDVs	Heavy-duty vehicles
ICEV	Internal combustion engine vehicle
TCO	Total cost of ownership
VECTO	Vehicle Energy Consumption Calculation Tool
WEO	World energy outlook
ZE	Zero-emission
ZEV	Zero-emission vehicle
ZLEV	Zero- and low-emission vehicle

1 Introduction

1.1 Background

Zero-emission vehicles (ZEVs) are widely regarded as an effective way to reduce CO_2 emissions and decarbonise the heavy-duty vehicle (HDV) sector. European truck manufacturers have announced ambitious plans to increase the sale of zero-emission trucks over the coming decade. According to their public statements, an estimated 4 - 9% of total truck sales would be zero emission by mid-decade, rising to 42 - 48% by 2030 and up to 60% for individual truck makers (T&E, 2021).

The heavy-duty trucking sector is a cost-sensitive industry. In contrast to passenger cars where upfront prices matter most to consumers, trucks are heavily-used capital goods which run over significantly higher mileages, making their total cost of ownership (TCO) the key decision-making factor for transport operators. Operational requirements such as vehicle range, recharging and refuelling times as well as payload are also important criteria when transitioning from conventional diesel trucks to ZEVs.

However, the speed at which the transition from internal combustion engine vehicles (ICEVs) towards battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) will happen in the heavy duty vehicle market, and for which vehicle segments, is still uncertain. Key drivers which will determine the market uptake include the expected technology improvements and cost reductions of vehicle components such as batteries, fuel cells and hydrogen storage tanks as well as the future development of energy prices including diesel, electricity and renewable hydrogen. Possible constraints such as insufficient vehicle ranges, insufficient charging infrastructure, additional downtime due to longer charging and refuelling times or payload losses due to heavier vehicles could potentially delay the market uptake.

1.2 Objective

To answer these questions, this report assesses the techno-economic feasibility and market uptake potential of zero-emission trucks for four different vehicle segments for the European Union (EU) and the United Kingdom (UK). From a market perspective, switching from ICEVs to ZEVs is considered feasible if TCO parity with diesel equivalents is reached and operational limitations such as range constraints, time or payload losses can be avoided. Based on the expected affordability and applicability, the analysis forecasts the ZEV uptake potential for each vehicle segment until the year 2040. A subsequent analysis also examines an accelerated market uptake scenario where policy measures such as vehicle purchase subsidies, CO_2-based road tolls and CO_2 pricing of transport fuels are taken into account.

1.3 Regulatory context

Besides economic and market developments, decisions by regulators have a strong influence on the pace of the transition. Effective, stringent and forward-looking regulation can accelerate the market uptake of ZEVs in the heavy-duty segment and can promote innovation and the timely development of affordable products. Besides policies which stimulate the demand for clean trucks and support the roll-out of charging and refuelling infrastructure, emissions performance standards or sales mandates requiring manufacturers to sell a certain share of ZEVs are considered effective instruments to increase the supply and bring down vehicle technology costs. A number of European governments has already indicated the ambition to transition to 100% ZE-HDV sales by 2040 including the UK, the Netherlands, Portugal, Austria, Finland and Luxembourg (Calstart, 2021).

In 2019, the EU adopted its first CO_2 standards for new HDVs[1]. The regulation requires manufacturers in Europe to reduce the fleet-wide average CO_2 emissions of their new vehicle sales by 15% until 2025 and by 30% until 2030 compared to a 2019/20 baseline.

The European Green Deal requires EU member states to reduce overall greenhouse gas (GHG) emissions by 55% by 2030 and make Europe climate-neutral by 2050. As a part of this, the European Commission will also review the HDV CO_2 standards and bring forward a proposal by the end of 2022. Elements of the review are expected to include (amongst other):

- Tightening the CO_2 target for 2030;
- Introducing CO_2 targets for 2035 and 2040;
- Adjusting the incentive mechanism for zero- and low-emission vehicles (ZLEVs);
- Including currently unregulated vehicle categories, such as small and medium lorries, vocational vehicles, buses and coaches as well as trailers;
- Assessing the potential role of so-called ‘renewable and low-carbon’ fuels.

1.4 Scope

European truck makers are now focussing on battery electric and fuel cell electric trucks in order to decarbonise their new sales. This is mainly due to the fact that these vehicle technologies offer significant CO_2 reduction potential, will be able to reduce trucking costs in the mid- and long-term and are technically and practically scalable. The report therefore focusses on the analysis of BEVs and FCEVs compared to their diesel counterpart.

Other vehicle technologies such as electric trucks powered by electric road systems (ERS) or ICEVs running on renewable hydrogen, e-fuels or biofuels are not part of the scope of the analysis. The same applies to potential measures to further increase conventional fuel efficiency, incentivise modal shift to rail and waterborne freight or improve logistics efficiency.

The analysis is carried out for the timeframe 2020 - 2040 and includes four vehicle segments and use cases which are aligned with the vehicle classification and duty cycles of the Vehicle Energy Consumption Calculation Tool (VECTO). The scope includes one rigid truck with an urban delivery duty cycle and three different articulated tractor-trailers (regional delivery, long haul and construction).

[1] Regulation (EU) 2019/1242

FCEVs are only taken into account for the articulated long haul and construction applications. Table 1 shows the assumed ranges of the vehicles that are assessed. These ranges are fixed over time. Therefore in this analysis, improved battery technology does not result in greater ranges but in lower vehicle prices for BEVs.

Table 1: Vehicle configurations of the four zero-emission reference vehicles and the corresponding ranges.

Vehicle type/GVW[2] – duty cycle	BEV medium battery	BEV large battery	FCEV
Rigid 16 tons - urban delivery	150 km	200 km	N.A.
Articulated 40/44 tons - regional delivery	300 km	400 km	N.A.
Articulated 40/44 tons - long haul	500 km	800 km	800 km
Articulated 40/44 tons - construction	150 km	300 km	300 km

All the vehicle and duty-cycle specific parameters are summarized in Table 2.

Table 2: Fixed vehicle parameters used for modelling the average energy consumption.

Configuration Duty cycle	Rigid – urban delivery	Articulated – regional delivery	Articulated – long haul	Articulated – construction
				
Wheel configuration	4x2	4x2 + standard semi-trailer	4x2 + standard semi-trailer	4x2 + tipper semi-trailer
Reference Payload	6,000 kg	12.900 kg	19,300 kg	19,300 kg

The techno-economic uptake potential is estimated for all of the EU countries and the UK. All analyses are performed for every individual country. Country-specific parameters taken into account are energy prices, vehicle deployment statistics and additional energy consumption due to differences in ambient temperature.

Besides a central scenario the effects of various policies on the uptake potential of ZEVs are assessed. This includes purchase subsidies, CO_2 pricing and road tolls. The ZEV uptake potential at country level is aggregated into:

- regions (as shown in Figure 1);
- an overall aggregated uptake potential for the whole of the EU+UK.

[2] Gross vehicle weight

Figure 1: Distinguished regions.

1.5 Methodology

In this report, the techno-economic uptake potential is based on two main parameters, i.e., the affordability and applicability of the three different drivetrains diesel, battery-electric and fuel cell electric. The affordability is as assessed on the basis of total cost of ownership, or TCO, and identifies the drivetrain technology that is most cost effective in terms of capital and operating costs. It is assumed that new vehicles are purchased by transport operators for a first use period of five years.

The second parameter, applicability, refers to the ability of a vehicle with a given range to perform a given transport operation. It is only considered for the BEVs as for both other drivetrain types it is assumed that the refuelling time does not significantly affect operations.

As a result, the techno-economic uptake potential of BEVs and FCEVs in a certain year corresponds to the share of the new registrations for which the BEV or the FCEV is the most cost-effective option and where the applicability of these options is ensured.

Market uptake potential vs. actual uptake
It is important to note that the forecasted market uptake potential is not necessarily equal to the actual uptake of ZEV drivetrain types into the future fleet, as this depends on a number of additional factors that are not accounted for in this analysis.

The working assumption is that a decision to buy a ZEV instead of a conventional diesel vehicle is purely driven by the TCO and the operational requirements in terms of vehicle range, charging and refuelling times as well as payload.

Other potentially limiting factors such as the availability of vehicles and infrastructure, funding and financing barriers or the acceptance by end users are not part of the quantitative analysis but are addressed qualitatively in section 8.

Figure 2 shows a schematic overview of the modelling approach to determine the techno-economic uptake. First the relevant vehicle characteristics are determined including vehicle power, mass, aerodynamics, tyre rolling resistance, and energy storage capacity (storage tank size and battery capacity). Dimensioning is based on an equal power-to-weight ratio (based on a truck at maximum payload) the three distinguished drivetrain types.

Based on these vehicle characteristics and the VECTO duty cycles, the energy consumption of each vehicle configuration is determined using a forward-calculating vehicle and powertrain simulation model. Combined with energy prices, this provides the energy cost. The vehicle characteristics feed in to determine the vehicle capital cost. Together with the energy cost and the other additional cost elements (e.g. assumed maintenance costs, tolling costs, etc.) they form the TCO. The maximum vehicle range of BEVs is derived from the assumed battery capacity and the determined energy consumption. This approach is explained in more detail in section 5.

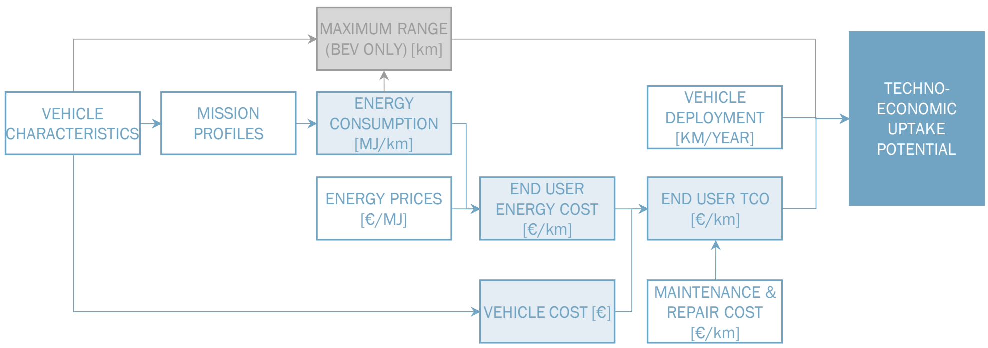

Figure 2: Schematic overview of the approach to determine the techno-economic uptake potential of zero-emission trucks.

All in all the favourable drivetrain is determined (based on affordability and applicability) for four vehicle types, for a large number of average daily distances (incremental steps of 25 km/day), for 28 countries, for 20 years.

1.6 Structure of the report

In section 2 the vehicle and powertrain dimensioning is reported, which results in relevant vehicle characteristics for the subsequent assessment of costs and feasibility. The energy consumption figures resulting from these characteristics and the duty-cycles are presented in section 3. This is followed by the determination of the TCO in section 4. Range requirements and the way that vehicles are currently being deployed are explained in section 5. The resulting market-driven techno-economic uptake potential is shown in section 6. Because of the large number of assumptions with significant uncertainties, a sensitivity analysis for several parameters is performed, which is included in section 6.3.

Additionally, an accelerated policy-driven uptake scenario had been developed, taking into account three different policy measures (purchase subsidies, CO_2-based tolling and CO_2 pricing on transport fuels), as explained in section 7. Other factors, besides affordability and applicability, that may influence a transport operator’s decision to acquire a truck with a certain drivetrain are further discussed qualitatively in section 8. Finally, conclusions and key findings are presented in section 9.

2 Vehicle characteristics

Determining the energy consumption and cost of the reference vehicles included in this assessment requires a clear dimensioning of relevant characteristics for the reference vehicles. This is done based on current technology characteristics for the reference vehicles in the year 2020, and assumptions on developments of the various technologies for these trucks are used to determine those for vehicles towards 2040. In this section, the 2020 reference vehicles are defined in terms of their relevant characteristics such as mass, power, aerodynamics properties and internal energy losses. Furthermore, the developments of those vehicles up to 2040 are determined taking account of dedicated energy efficiency improvements (e.g. aerodynamics and low resistance tyres) and technology improvements that affect the vehicle's energy consumption (e.g. increasing energy density of batteries).

2.1 Drivetrains

2.1.1 *Diesel powertrain*

The diesel trucks make use of a conventional drivetrain entailing a diesel engine delivering power to a 12-speed gearbox and a fixed reduction to the driven wheels. Energy regeneration is not possible in this drivetrain. Auxiliaries are connected to the mechanical output of the engine. Note that for example the heating of the cabin is a direct waste product of the combustion process and does therefore not impact the energy consumption of the truck.

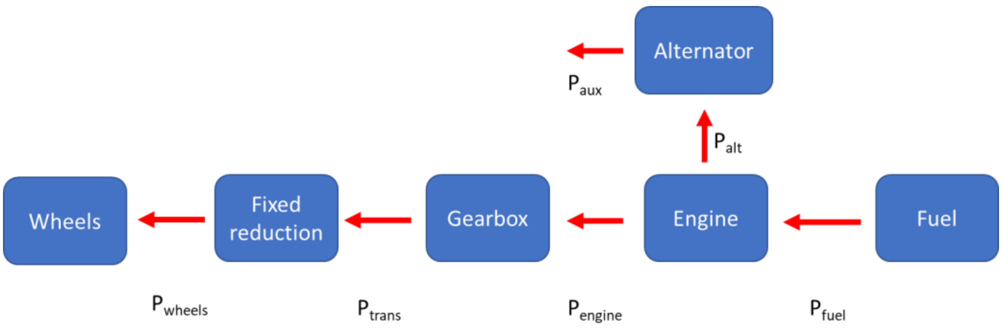

Figure 3: Diesel vehicle modelling architecture.

2.1.2 *BEV powertrain*

The battery electric powertrain is assumed to use an electric permanent magnet synchronous machine (PMSM) as the mechanical power source. Electrical power is supplied by a nickel-manganese-cobalt (NMC) or lithium-ion-phosphate (LFP)[3] battery trough an inverter. Mechanical power is delivered through a 2-speed gearbox and a fixed reduction to the driven wheels of the truck.

As the electric machine is capable of both motoring and generating operation, energy regeneration from braking is possible. In contrast to the conventional diesel drivetrain, auxiliaries consume electrical power directly from the battery or inverter. In the absence of waste heat from a combustion engine, cabin heating is provided by a heat pump which also consumes electrical power.

[3] Battery losses are always modelled based on NMC loss properties.

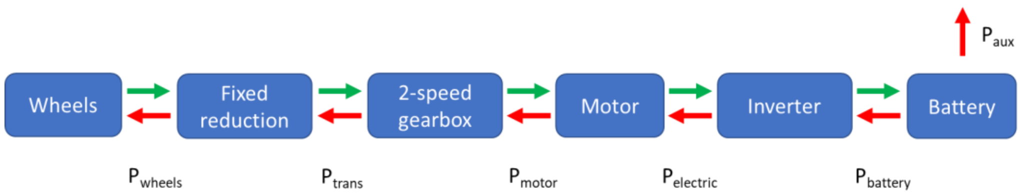

Figure 4: Battery electric vehicle modelling architecture.

2.1.3 *FCEV powertrain*

The fuel cell electric powertrain is similar to the BEV powertrain. The main difference is observed in the electric power supply which consists of both a battery and a fuel cell. The fuel cell is seen as the main electric power supply in the fuel cell truck. Fuel cells are not well suited for transient use. As such the fuel cell ideally is used in steady state operation, which is also favourable from an energy consumption point of view. Therefore, a battery is used as a buffer in the electrical system. The battery is sized such that the peaks in required driving energy are shaved. In optimizing the efficiency of the fuel cell electric truck, control of the power split between the battery and the fuel cell is critical. For the fuel cell truck model, a modular equivalent consumption minimization strategy (ECMS) controller (TNO, 2019) is used to allow for optimal power split.

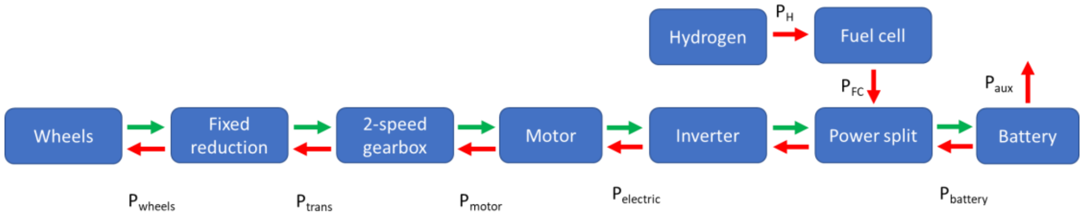

Figure 5: Fuel cell electric vehicle modelling architecture.

2.2 Vehicle dimensioning

The analysis of the ZEV uptake potential in this report is based on four reference vehicles based on two different vehicle types, as indicated in the scope:

- 16-ton rigid truck corresponding to VECTO group 3
- 40/44-ton articulated tractor-trailer corresponding to VECTO group 5

The configuration of the articulated tractor-trailer is based on the vehicle use cases as shown in Table 2. The reference vehicles are dimensioned specifically for each powertrain option and use-case presented in Table 1. Dimensioning starts with the reference year of 2020, for later years the dedicated energy-efficiency improving measures presented in section 2.3 are subsequently implemented. Also effects of technology developments that affect the vehicle's energy consumption are taken into account (e.g. increased energy density of batteries).

Dimensioning of the diesel truck is based on the standard vehicle in VECTO as described in the report for supporting the impact assessment for CO_2 emissions standards for Heavy Duty Vehicles (TNO, 2018). For the dimensioning of the 2020 BEV and FCEV trucks the same glider (i.e. the truck without drivetrain) is assumed as for the diesel truck.

2.2.1 *Power-to-weight ratio*

The power-to-weight ratio is set to be equal for the three drivetrain types assessed, based on a truck at maximum payload. The assumed ratios in 2020 are shown for each of the four vehicle categories in Table 3. These levels are based on the 2020 reference diesel vehicles. For the trucks in later years the same power is assumed as for the 2020 reference, effectively leading to a slight increase in the power-to-weight ratio due to decreasing weight. If this weight reduction would have been taken into account, vehicles could have been dimensioned slightly lighter and cheaper, therefore resulting in slightly lower TCO for BEVs.

Table 3: Power to weight ratio of the 2020 reference trucks based on the truck-trailer maximum mass.

Vehicle type	Power to weight [W/kg]
Rigid urban	11.25
Articulated regional	8.75
Articulated long haul	8.75
Articulated construction	8.75

2.2.2 *Vehicle power*

The vehicle power is derived from the set power-to-weight ratios in Table 3 and the given gross weight of the vehicles. The EU Weights and Dimensions Directive[4] grants an up to two-tonne additional maximum weight allowance for ZEVs and allows for longer vehicles for improved aerodynamic performance, energy efficiency and safety (EU, 2019). Fuel cell power and hydrogen capacity are sized to be able to deliver the mean constant power drawn during driving (including the demand from road slopes) and to fulfil the range requirements[5], respectively. This results in power levels as shown in Table 4.

Table 4: Truck engine power

Engine power [kW]	Diesel	BEV-M	BEV-L	FCEV
Rigid urban	180	190	190	-
Articulated regional	350	370	370	-
Articulated long haul	350	370	370	370
Articulated construction	350	370	370	370

2.2.3 *Vehicle mass*

As explained in section 1.4, the ranges of the vehicles are fixed over time. The battery capacities of the BEVs are determined in such a way that these ranges are met. The impact of the battery mass on the energy consumption of the truck is taken into account.

[4] Council Directive 96/53/EC and amendments

[5] Note that the sizing of the power for the fuel cell is done in such a way that the vehicle is capable of the same performance as a comparable diesel truck. Even if the FCEV is operated in a mountainous area with higher road slopes, the performance in terms of vehicle speed will be similar.

2.2.3.1 *Vehicle mass excluding battery*

The glider masses of the vehicles with the various drivetrain types are assumed to be equal. Based on (Basma, Beys, & Rodriguez, 2021), the mass of the electric drivetrain excluding the battery is assumed to be 1550 kg lower than that of the diesel drivetrain for the articulated truck. For the rigid truck, this difference is derived by scaling with the empty tractor masses of the articulated and rigid diesel truck respectively, resulting in an 880 kg lighter drivetrain for the BEV (excluding the battery).

The mass of the fuel cell drivetrain components is calculated according to (Marcinkoski, Vijayagopal, Kast, & Duran, 2016). The mass of the fuel cell system and the mass of the hydrogen storage tank in the 2020 reference vehicles is shown in Table 5.

Table 5: Hydrogen component masses 2020.

Hydrogen component masses 2020 [kg]	Fuel cell system mass	Hydrogen storage tank mass
Articulated long haul	584	1300
Articulated construction	584	572

2.2.3.2 *Battery capacity and mass*

The battery capacity for the BEVs is selected such that the assumed ranges can be met. The energy consumption increase due to the mass of the battery is accounted for. This is done by determining the energy consumption (as further explained in section 3) for multiple battery sizes until the battery size is found for which the corresponding energy consumption results in the desired range. The required nominal battery capacity for each vehicle is shown in Table 6. Due to improved energy efficiency of the vehicles and energy density of batteries, the required battery capacity reduces over time. This is further explained in section 2.3.

As further explained in section 4.2.1 and 4.2.2, a maximum depth of discharge of 90% is assumed. This means that the values shown in Table 6 include 10% unusable battery capacity. Moreover an additional 25 km safety margin is included to prevent end users being stranded with a depleted battery. This additional capacity never has to be drawn from in any of the analysis performed in this study.

The assumed battery capacity for the FCEVs is 140 kWh for both fuel cell reference vehicles. This capacity ensures that the full potential of regenerative braking can be exploited and that the fuel cell can be run in steady state operation. Note that battery capacities are not restricted by mass or volume in this report. The effects of this on payload penalty are described in section 2.4.

Table 6: Required nominal battery capacity for the battery electric truck including energy density improvements of batteries as shown in section 4.2.1.

BEV trucks	Size	Range [km]	Nominal battery capacity [kWh]		
			2020	**2030**	**2040**
Rigid urban	Medium	150	126	110	109
	Large	200	155	139	139
Articulated - regional	Medium	300	429	350	349
	Large	400	569	465	459
Articulated - long haul	Medium	500	777	627	616
	Large	800	1243	966	946
Articulated - construction	Medium	150	281	253	252
	Large	300	520	457	441

2.2.3.3 *Overall vehicle mass*

The overall masses of the rigid truck and the tractor-trailer combinations including batteries in the year 2020 are presented in Table 7. The main sizing parameters of the reference vehicles are shown in Table 24 to Table 27 of Appendix A.

Table 7: Empty weight in kg of the rigid truck and tractor-trailer combinations for 2020, 2030 and 2040

Parameter	Drivetrain	2020	2030	2040
Rigid Urban Truck	Diesel	4,669	4,436	4,436
	BEV medium	4,474	3,992	3,700
	BEV large	4,631	4,096	3,780
Articulated Truck Regional Delivery	Diesel	15,729	15,318	15,318
	BEV medium	16,511	15,095	14,439
	BEV large	17,271	15,506	14,732
Articulated Truck Long Haul	Diesel	15,729	15,318	15,318
	BEV medium	18,402	16,084	15,149
	BEV large	20,934	17,295	16,027
	FCEV	16,884	16,083	15,609
Construction Truck	Diesel	14,329	13,918	13,918
	BEV medium	14,306	13,349	12,781
	BEV large	15,605	14,077	13,284
	FCEV	14,722	14,075	13,606

2.3 Vehicle improvements

The efficiency of vehicles is expected to improve over time until 2040. In a previous study by TNO, multiple energy efficiency improving technologies were examined and an impact assessment was performed (TNO, 2018). Energy efficiency improving technologies range from aerodynamic measures such as the addition of roof spoilers to an reduction in tyre rolling resistance and the reduction of the mass of vehicles due to more lightweight design. A selection of the energy reduction technologies described in that report is applied to the reference trucks throughout the years as shown in Appendix **B**.

Note that technologies are only applied when it can be expected that this technology is used across the entire fleet for each reference vehicle. The efficiency improvements for the years between 2020 and 2030 as well as 2030 and 2040 have been linearly interpolated. Note that the majority of efficiency improvements is expected between 2020 and 2030. Improvements after 2030 are assumed to decrease significantly as the marginal cost of additional energy efficiency technologies for the diesel trucks that could still be expected beyond 2030 might not be fully amortised through lower energy costs. Partly therefore, vehicle manufacturers are expected to comply with the reduction targets under the CO_2 standards by selling an increasing number of ZEVs instead of further improving the fuel efficiency of ICEVs. The list of specific measures and the resulting effects is presented in Appendix **B**.

2.4 Reference payload and payload penalty

2.4.1 Reference payload

The assumed reference payloads shown in Table 8 are used to determine the energy consumption of the trucks. The reference payloads of the BEVs and FCEVs are assumed to be equal to the payloads of the equivalent diesel trucks in order to meet the same operational needs and are kept constant over time. More detail on the assumption for battery chemistry and the resulting mass of the battery packs for the BEVs can be found in section 4.2.1.

Table 8: Payload masses used to determine the energy consumption of the reference vehicles.

Reference vehicle	Payload mass [kg]
Rigid urban	6,000
Articulated regional	12,900
Articulated long haul	19,300
Articulated construction	19,300

2.4.2 Payload penalty

The payload penalty is defined as the reduction of payload compared to the maximum payload due to weight restrictions. The reference payloads as shown in section 2.4.1 are lower than the maximum payloads. The battery electric trucks for the urban, regional and construction duty cycles have no penalties on the maximum payloads, even in the year 2020. For the long haul truck however, this is the case for the early years. Despite the additional weight allowance for zero-emission trucks (EU, 2019), the large batteries required in the early years in combination with the relatively low energy density of batteries result in a temporary penalty on the maximum for the long haul BEVs. As shown in Figure 6, the long haul BEV with the large battery has a penalty of 3200 kg on the maximum payload in 2020 which reduces to zero by 2030. Similarly, the medium battery version has an initial payload penalty of 670 kg in 2020. Its payload penalty decreases to zero by 2024. The mass of the FCEV drivetrain for the long haul truck is low enough not to result in any payload penalty, partly due to the increased weight allowance of zero-emission trucks.

The limited payload losses in the early years are not taken into account for the applicability of long-haul BEVs. The reason for this is that the majority of road freight movements in Europe are volume- instead of weight-constrained.

Furthermore a proportion of vehicle trips are carried out only partially loaded or even empty. Statistics by the UK's Department of Transport estimate that 30% of long haul trucks are driving empty while the average loading factor (by weight) of the fleet is 63% (Department of Transport, 2020). Another study by Hill et al. estimates that the share of vehicle-kilometres performed by long haul trucks above 32 tonnes GVW, which is constrained by weight limitations, is only between 10% and 19.5%, while the average loading factor was estimated to be around 56% (Hill, 2017).

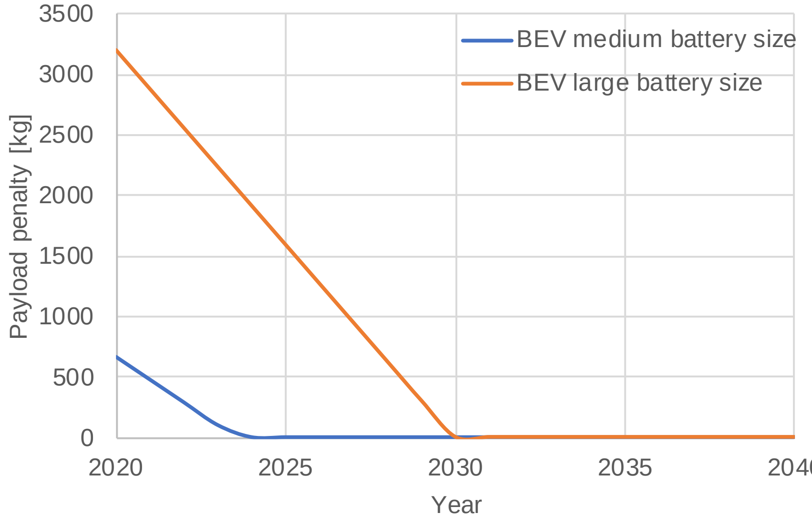

Figure 6: Payload penalty for the BEV long haul articulated trucks.

It should be noted that potential volume constraints or individual axle weight limitations resulting from the installation of large batteries for BEVs or hydrogen storage tanks for FCEVs have been taken into account in this report.

3 Vehicle energy consumption

3.1 Modelling approach

The energy consumption of a truck is an important factor in determining the operating costs of a vehicle. In this report, vehicle energy consumption is derived from the TNO model ADVANCE (TNO, 2002). This is a modular simulation tool which takes detailed vehicle parameters into account, such as the losses in the vehicle powertrain and external loss factors such as aerodynamic and tyre rolling resistance on a pre-defined trip profile. Input for this model is the vehicle dimensioning as discussed in section 2. As mentioned in section 1.4, different vehicle segments are considered, i.e. urban delivery, regional delivery, long haul and construction. For each segment, the standardised duty cycle as defined in VECTO is applied (EU, 2017), specifying the velocity and road slope during a reference trip.

The main calculation elements for the energy consumption calculation are described in section C.1 of Appendix C. Assumptions regarding parameter values for aerodynamics, road loss properties, auxiliary power consumption and efficiency of various components are described in more detail in Appendix C.

3.2 Energy consumption

Based on the calculation steps and the parameter assumptions as described in Appendix C, the ADVANCE simulation model has been configured and run for each configuration, i.e. the combination of drivetrain type and mode of deployment. The model has been run for the years 2020, 2030 and 2040, for intermediate years the energy consumption has been interpolated linearly. The output of the model is the mean energy consumption for each of these configurations including the charging losses (‘charger-to-wheel’), which feeds into the TCO calculations (see section 4). The results are presented graphically in Figure 7 for the years 2020, 2030 and 2040 and numerically in Table 9.

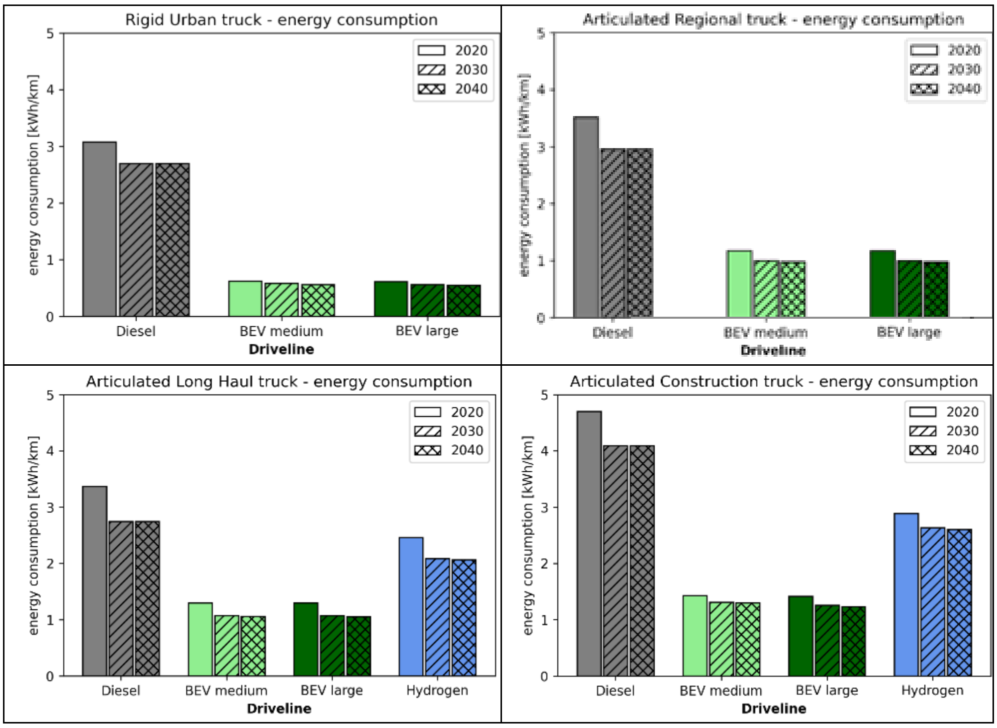

Figure 7:Determined energy consumption of the four assessed heavy duty vehicle types for the various drivetrain types.

Table 9: Energy consumption for the various vehicle configurations and drivetrain combinations as modelled with TNO's ADVANCE model (tank-to-wheel / charger-to-wheel).

Configuration	Drivetrain	Unit	2020	2030	2040
Rigid urban	Diesel	l / 100km	30.8	26.9	26.9
	BEV medium	kWh / 100km	62.5	58.6	56.4
	BEV large	kWh / 100km	61.9	56.1	55.0
Articulated regional	Diesel	l / 100km	35.2	29.6	29.6
	BEV medium	kWh / 100km	116.9	98.9	97.2
	BEV large	kWh / 100km	116.9	99.2	97.2
Articulated long haul	Diesel	l / 100km	33.7	27.5	27.5
	BEV medium	kWh / 100km	129.4	107.5	105.8
	BEV large	kWh / 100km	130.6	105.6	102.8
	FCEV	kg / 100km	7.4	6.3	6.2
Articulated construction	Diesel	l / 100km	47.1	40.9	40.9
	BEV medium	kWh / 100km	143.3	130.8	129.7
	BEV large	kWh / 100km	141.4	126.1	123.1
	FCEV	kg / 100km	8.7	7.9	7.8

The final energy consumption of the BEVs is up to three times lower than for conventional diesel trucks (based on the caloric value of diesel fuel). FCEVs have a final energy consumption of about two thirds compared to the diesel truck.

These differences are the result of the much lower efficiencies of internal combustion engines as compared to battery electric and fuel cell drivetrains as well as of the regenerative braking capabilities of the electric powertrains.

The results for the energy consumption of the diesel truck can be benchmarked against the analysis of the truck monitoring and reporting data by the Joint Research Centre (JRC) (Broekaert & Fontaras, 2022). With 33.63 l/100km for regional delivery and 29.87 l/100km for long haul respectively in that report, the modelling results are somewhat higher yet corresponding quite well.

Note that for the battery electric vehicles, the energy consumption of the large battery vehicles is slightly lower than that of the medium battery vehicle. This is due to the higher battery charging and discharging efficiency for the large BEV.[6]

3.3 Effects of temperature differences for BEVs

The modelled air temperature corresponds to the standard atmospheric condition of 15°C and an ambient air pressure of 1013.25 hPa (ISO 2533:1975). Different ambient conditions can significantly affect the energy consumption of especially battery electric vehicles. At lower temperatures, both an increase in air resistance due to higher air density and a lower efficiency of battery systems result in higher energy consumption. Also using a cabin heater or air-conditioning system results in temperature dependent energy consumption. Due to these non-linear temperature effects, a calculation of the energy consumption for the yearly average temperature would be lower than the actual representative average energy consumption when taking into account the spread in daily temperatures found during the year and within the different countries.

Effects of ambient temperatures on energy consumption are taken into account based on modelling done by the ICCT (ICCT, 2021a). In that study, the additional energy consumption has been determined for trucks with different battery sizes at various temperatures. The results of this study are shown in Figure 8.

The ‘representative’ temperatures that are used in this study are provided in Table 54 in Appendix K. These are based on the temperatures in the country’s capitals (World Meteorological Organization , 2022). Since trucks drive more during the day than during the night, the maximum temperature is given twice the weight of the minimum temperature to determine the ‘representative’ temperature.

The additional energy consumption due to temperature effects is based on the month in which the additional energy consumption is the highest. The reasoning here is that trucks also have to be deployable in periods of cold or hot weather. For countries with low minimum temperatures, e.g. Finland, this is the month with the lowest ‘representative’ temperature. For countries with high maximum temperatures, e.g. Greece, this is the month with the highest temperature. The resulting additional energy consumption per country for different vehicle types with various battery sizes is provided in Table 55 and Table 56 of Appendix K.

[6] This effect is higher than the additional road load from the higher inertia and rolling resistance. In practice, the larger battery pack will probably be charged using a higher current to facilitate shorter charge times. This may cancel out the higher efficiency of the large battery vehicle.

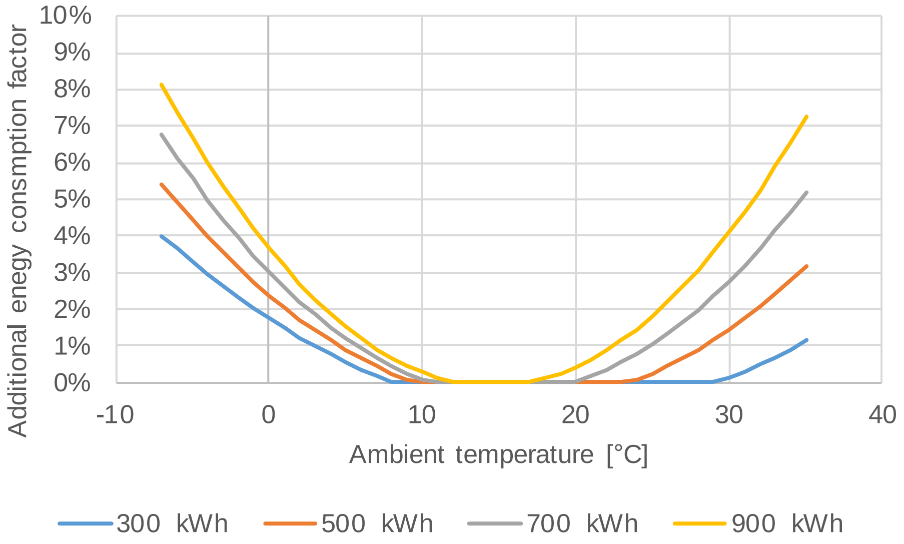

Figure 8: Effects of ambient temperature on energy consumption for battery-electric trucks with various battery sizes, based on (ICCT, 2021a).

High and low ambient temperatures also result in higher energy consumption for ICEVs. Low temperatures directly result in lower fuel efficiency due to the higher air drag while using mobile air conditioners at high temperatures lead to a fuel penalty. These effects are not taken into account, but would have been favourable for the TCO and therefore the uptake potential of ZEVs.

4 Total cost of ownership

The TCO of a vehicle consists of all costs during a certain use period. In this report the TCO includes purchase costs, energy costs and maintenance costs. Other costs like labour, overheads and insurance costs as well as vehicle taxes are assumed to be the same for all drivetrain types and would therefore not affect the TCO comparison. For that reason, these costs are not explicitly accounted for in the TCO calculation. In this section, all relevant assumptions regarding vehicle prices, energy costs and maintenance costs as well as results are presented for each of the vehicle configurations.

In order to verify the modelling approach, three stakeholder consultations with vehicle manufacturers were held during the course of the project. In addition, a workshop with stakeholders from the research community was organised. The purpose of these consultations was to receive feedback on the TCO input parameters, and to gather expert opinions on a range of questions.

The consultations provided highly valuable information and insights, which were used to modify and improve the input parameters where necessary. Due to the confidential setting in which the information was shared, the names of the stakeholders and the inputs which they provided are not disclosed in this report.

4.1 Modelling parameters and assumptions

Table 10 contains an overview of the modelling parameters which are used in this report for the TCO calculation.

Table 10: General TCO modelling parameters.

Parameter	Value
Timeframe	2020 – 2040
Operational days per year	265 days
Perspective	First use period of 5 years
TCO Method	Net Present Value (NPV) with discounted cash flows
Discount rate (IRR)	9.5%
Residual value	37.5% fixed rate + ‘x’ variable rate
Maintenance costs	included
Cost of capital	excluded
Vehicle registration and circulation taxes	excluded
VAT	excluded
Taxes: excise duty on diesel and unrecoverable taxes and levies on electricity	included
Personnel costs	excluded
Overheads	excluded
CO_2 pricing, purchase subsidies, CO_2 based tolling	included only in specific policy scenarios, not in the central scenario

These parameters and the assumptions made in this report are further explained below:

- The model is applied over the timeframe between 2020 and 2040. For each year the TCO is computed for all vehicle configurations.
- We assume on average of 265 operational days per year. The operational days are required to convert the yearly mileage into an average daily mileage.
- The TCO is computed from the perspective of the first use period of five years. This is done since the result is used for an estimation of the uptake potential for new vehicle sales.
- The residual value of the vehicle is dependent on the mileage driven during the first 5 years. Similar to the method proposed in (ICCT, 2021) a fixed depreciation rate is assumed of 7.5% per year (37.5% after 5 years) and a variable depreciation rate is used which is based on the mileage of the truck.
- It is assumed that a vehicle has no residual value after a lifetime mileage of 1.49 million kilometres. This is the distance reached when driving on average 1150 km per day for 5 years. A linear interpolation is applied to estimate the residual value for a varying vehicle deployment. The residual value after 5 years ranges linearly from 61% at 25 km/day to 8% at 1000 km/day.
- A discount rate of 9.5% is applied for future cash flows, which is in line with the approach in (ICCT, 2021). No investment interest rate is applied on the vehicle cost.
- Vehicle registration and circulation taxes are not taken into account.
- VAT on vehicle purchase, personnel costs and overheads are also excluded.
- Excise duty on diesel and any fuel rebates are included in the diesel price, also unrecoverable taxes and levies are included in the electricity price.

4.2 Vehicle prices

Vehicle prices are modelled bottom-up, meaning that for each specific truck the vehicle costs are built up based on the components as shown in Table 11. The component costs are based on a review of existing literature. Costs are presented at the price level of 2020 euros. Prices are adjusted based on the European HICP index (ECB, 2022). For an overview of sources used see Appendix E. Vehicle costs are assumed to be the same across Europe.

Table 11: Input parameters for the cost modelling approach.

Input parameter	**Diesel**	**BEV**	**FCEV**
Glider	x	x	x
Auxiliaries	x	x	x
Trailer	x	x	x
Battery		x	x
Fuel tank	x		x
ICE and exhaust aftertreatment system	x		
Electric motor		x	x
Fuel cell system			x
Energy efficiency technologies	x	x	x
Other components (e.g. DC/DC converter, onboard charger and air conditioning / heatpump and compressors)		x	x
Mark-up factor	x	x	x

Certain costs are independent of the vehicle characteristics such as the glider[7] and trailer costs (for the tractor-trailer combinations). Other costs scale with drivetrain-specific parameters, such as battery costs which scale with battery size, and internal combustion engine or electric motor costs which scale with power. Apart from these components, also the costs of energy efficiency improving technologies are considered. Based on the configuration of the vehicle, a total vehicle price is calculated. Adding a mark-up factor to these costs results in the vehicle pre-tax retail price (see section 4.2.7).

4.2.1 Battery

Battery costs are based on Bloomberg NEF (BNEF) projections (BNEF, 2021). While there are numerous battery price projections available in the literature, most of these make extrapolations based on the past and do not include future developments, for instance such as the integration of battery cells directly into the vehicle chassis which results in further cost reductions. BNEF takes stock of future developments while the price projections are transparent, both of which were reasons to use the BNEF data in this project.

BNEF provides volume-weighted average pack price projections for passenger cars until 2035 based on expected demand for lithium-ion batteries and an observed learning rate. In terms of used battery chemistries, it is assumed for this analysis that 80% of the cell volume market in the heavy-duty segment will be NMC, whereas the remaining 20% will be LFP. This split has also been applied to calculate chemistry-weighted prices and energy densities (BNEF, 2021a). The assumed energy densities increase over time, as shown in Table 12. The mass of the battery packs for the BEVs and the effect on payload are based on these densities (see section 2.4).

Table 12: Assumed battery-pack energy densities based on 80% NMC/20% LFP volume split.

Battery-pack energy density [Wh/kg]	**2020**	**2025**	**2030**	**2035**	**2040**
Weighted average	184	232	280	328	376

To convert passenger car battery costs to heavy-duty battery costs a multiplier has been introduced. For the years up until 2021 the multiplier for heavy-duty battery costs compared to passenger car battery costs can be deduced from observed prices. Towards the future it is expected that this multiplier will decrease due to higher production volumes of heavy-duty batteries. It is assumed that in 2030 heavy-duty batteries will cost about 13% more compared to the volume-weighted average of passenger car batteries. This premium is partly due to a different weighting between NMC and LFP market volume shares and partly due to the adaptations needed for NMC batteries to be applicable for heavy-duty vehicles (e.g. chemistry changes).

Between 2020 and 2030 this factor decreases exponentially, after 2030 the multiplier is assumed to be constant at 13%. For the years beyond 2035 it is assumed that the learning rate of 18% for the pack price development decreases to 1% in 2040. In other words, battery prices would reach a floor value because of the required raw materials, production processes and electricity needs.

[7] Glider means the truck cab and chassis, without the drivetrain

Since the battery pack price is one of the main influencing factors in the price for battery electric trucks, a sensitivity analysis is performed using a lower 17% learning rate until 2035 instead of 18% (see section I.1/ Appendix I). The battery pack price projections that are used in the cost calculations are visualized in Figure 9.

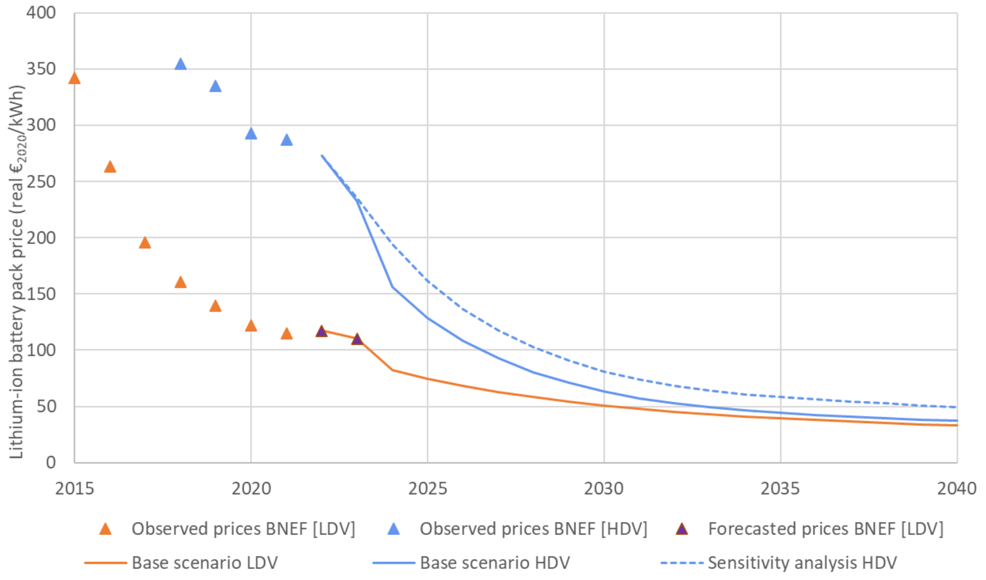

Figure 9: Battery pack price projection for HDVs until 2040 based on BNEF, edits by TNO.

4.2.2 Battery degradation

The SoH of a battery is heavily influenced by the Depth of Discharge (DoD), charge, discharge rates and operating temperatures (Harlow J. E., 2019). As mentioned in section 2.2.3.2, a 90% DoD is assumed in this study. This means that 90% of the nominal battery capacity can be used. The buffer of 10% is needed to avoid any accelerated battery degradation. In order to avoid being stranded with a depleted battery, an additional safety margin of 25 km range is accounted for.

Research shows that depending on depth of discharge, charge and discharge rates and temperature, up to 3000 Equivalent Full Cycles (EFC) could be possible for NMC cells. For LFP batteries the number of cycles is higher compared to NMC cells (Preger, 2020) (Harlow J. E., 2019). In this report, a mix of both LFP and NMC cells are modelled as explained above.

Based on the ranges for BEVs (Table 1) and the battery sizes (Table 6) the number of equivalent full cycles required during the first use period of 5 years have been calculated for each BEV. In order to take into account that the battery capacity decreases over time it is assumed that a linear battery degradation towards a SoH of 80% after 3000 cycles takes place. The resulting number of necessary equivalent full cycles during the first use period are presented in Table 13. The effect of battery degradation on the usability of trucks is not taken into account in this study. However, other factors that affect the way that trucks are being used in a similar way are assessed in section 6.3.

Based on the cited literature above and the number of cycles necessary, it is assumed that batteries do not have to be replaced during the first use period as the required number of cycles is always significantly lower than what the current research suggests. If future research shows evidence that this assumption does not hold this would have a significant impact on the results presented in this report.

Table 13: Number of Equivalent Full Cycles necessary for daily range during the first use period of five years.

BEV trucks	**Size**	**EFC necessary during first use period**		
		2020	**2030**	**2040**
Rigid urban	Medium	1,170	1,280	1,230
	Large	1,870	1,900	1,860
Articulated regional	Medium	1,210	1,260	1,240
	Large	1,190	1,240	1,230
Articulated long haul	Medium	1,200	1,240	1,240
	Large	1,200	1,240	1,250
Articulated construction	Medium	1,210	1,230	1,220
	Large	1,210	1,230	1,240

4.2.3 *Fuel cell*

In the literature review a large spread for fuel cell costs was found. This may in part be due to the fact that some sources provide only fuel cell stack costs while others present fuel cell stack system costs which may be up to two times higher (Wang, Wang, & Fan, 2018). In this report the price of the entire fuel cell system is taken into account.

Fuel cells are currently produced at low volumes which means that costs are relatively high. Similar to battery costs, future cost reductions for fuel cells are heavily dependent on higher production volumes at a global level. Future uptake of FCEVs in the light-duty vehicle segment is uncertain, also given that currently battery technology seems to be ahead of hydrogen technology due to the increasing scale in the passenger car market.

Based on sources found in the literature review that do provide assumptions on scale of production (Roland Berger, 2020) (James B. D., 2021) (James B. D., 2018), combined with assumptions for production levels over time, a cost projection of the fuel cell system was deducted. The reductions in the cost development for fuel cells towards 2030 are in line with the projections made in a study by (Ricardo, 2021). The results are presented in Figure 10 where the bandwidth is based on a relevant selection of literature sources, and the coloured lines indicate the applied cost for fuel cell systems over time.

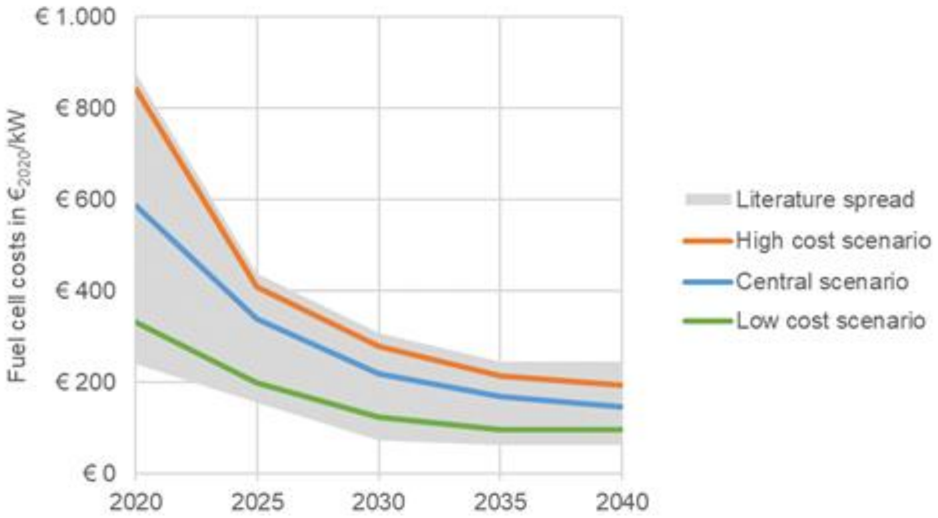

Figure 10: Development of fuel cell system costs per kW in $€_{2020}$.

4.2.4 *Energy efficiency improving technologies*

Apart from the main components necessary to be fully functional, heavy-duty vehicles will also be equipped with components that decrease energy consumption (see section 2.3 for the potential of these technologies). For 2020 only a few of these technologies are applied and at a low penetration level. Towards 2030 more technologies are expected to be applied and the level will increase to full penetration. The costs of the energy efficiency technologies are based on a previous study by (TNO, 2018)[8]. An overview of the applied energy efficiency improving technologies is included in Appendix **B**. The cost per technology for specific vehicle groups is provided in Appendix **E**.

4.2.5 *Glider and other components*

The glider consists of the vehicle chassis and the cab, excluding the powertrain. These costs are usually a little higher for rigid trucks as compared to tractor trucks because the glider for rigid trucks is larger. For diesel trucks a number of auxiliary systems are mounted on the diesel engine which receive power from the drivetrain, for instance the cabin is heated by the waste heat from the combustion process. For a battery electric truck and a fuel cell electric truck this is not possible, which entails that these auxiliary systems need to be added separately. Examples of such auxiliary systems are a heat pump and electric air brake compressors. These auxiliary systems are assumed to be included already in the glider costs for diesel trucks while for electric trucks they are added separately. This is why in this report a slightly less expensive glider is assumed for the BEVs and FCEVs compared to the diesel trucks.

Apart from auxiliary systems necessary in all drivetrains there are also drivetrain-specific components which are required to operate the vehicles. For a diesel truck this includes for instance the diesel fuel tank and the exhaust aftertreatment system, while for the FCEV this is the hydrogen storage tank and for the BEV the onboard charger. An overview of sources for the glider and the auxiliary component costs is provided in Appendix E.

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[8] For the VECTO group 3, the cost of energy efficiency technologies and prices for group 4 are used since group 3 is not part of (TNO, 2018).

4.2.6 *Drivetrain*

An overview of the drivetrains included in this report is given in section 2.1. For diesel trucks the drivetrain costs are assumed to include both engine costs and gearbox costs. The costs of the electric drivetrain consist of electric motor costs based on costs per unit of power (kW) and costs for auxiliaries that scale with power. Auxiliaries as such includes the battery management and high-voltage system costs (Ricardo, 2021). Over time, the cost for the electric drivetrain is expected to decrease by about 75% compared to the cost estimated for 2020 (Ricardo, 2021).

Drivetrain costs for the FCEV include fuel cell costs, as discussed in section 4.2.3, and costs for the electric drivetrain, which are the same (per unit of power) for both the BEV and FCEV. This means that for trucks with the same power, FCEVs have a cost offset compared to BEVs based on the costs of the fuel cell. At the same time hydrogen trucks require a smaller battery which leads to lower costs. Apart from range limitations with regard to the deployment, the competitiveness of FCEVs compared to BEVs is mainly determined by the future costs of fuel cells as compared to future battery costs.

4.2.7 *Mark-up factor*

After all component costs are aggregated into the total vehicle cost, the pre-tax retail price is calculated by multiplying the total cost with a mark-up factor.

The mark-up factor accounts for indirect costs such as:

- Assembly costs
- Research and development costs
- Marketing costs
- Distribution costs
- Profit, both for manufacturer and retailer

Mark-up factors are for most cases not readily available, and OEMs are reluctant to provide such information as this is understandably sensitive from a competitiveness point of view. Reasons that mark-up factors are hard to assess are that they depend on multiple factors such as the riskiness of the applied technology, the maturity of the market, the level of vertical integration and the extent to which OEMs make use of cross-subsidizing to optimize profits and market shares.

Whereas the market for diesel trucks is mature and the risk of the technology is low, for zero-emission drivetrains the market is still developing, and the technology risk is higher. To take stock of this effect in this analysis it has been decided that the current mark-up factor for diesel trucks is significantly lower compared to the mark-up factor for battery electric of fuel cell electric trucks.

For diesel trucks the mark-up factor is calculated by dividing a representative vehicle retail price of a truck in VECTO group 5 tractor without trailer (at € 100.000) by the bottom-up vehicle cost. This results in a mark-up factor of 19% for diesel trucks. This mark-up factor is applied to all diesel vehicles in the reference year 2020.

For the zero-emission drivetrains, the mark-up factor for 2020 is expected to be significantly higher due to lower production volumes. A value of 40% is assumed for 2020, based on a recent study by the ICCT (Sharpe, 2022).

Over the next decades, the production volumes of diesel trucks are expected to decrease significantly while those of zero-emission trucks will scale up. As a result, economies of scale of diesel drivetrains and zero-emission drivetrains can be expected to reach the same order of magnitude. Therefore, the mark-up factor of the various drivetrains is assumed to reach a value of 25% in 2040, see Figure 11.

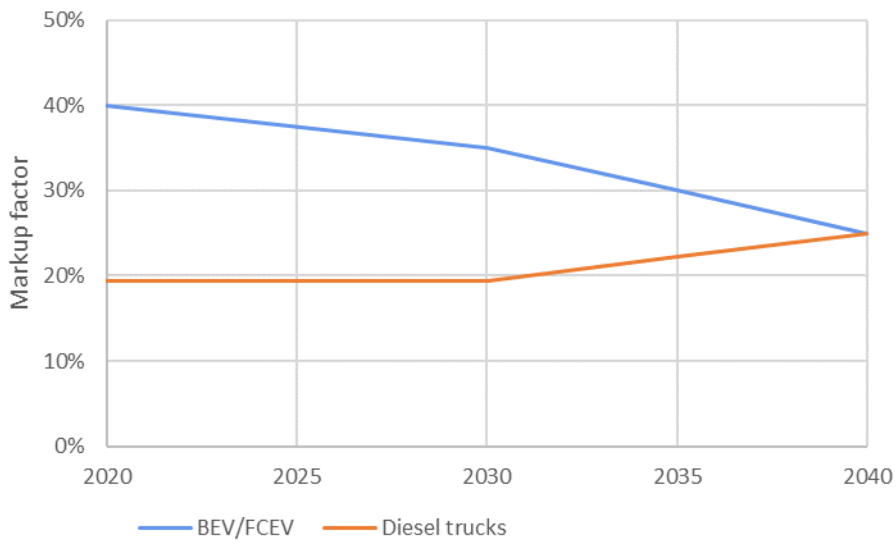

Figure 11: Mark-up factor assumptions used for the cost modelling in this report.

4.2.8 *Trailer*

The assumed costs of a single trailer are based on three recent studies by the ICCT (2021b) (2018) (2017). For the articulated trucks, a trailer-to-tractor fleet ratio of 1.4 is used, meaning that for every new tractor truck there are on average 1.4 trailers entering the fleet. This value is based on a 2018 study by the ICCT (ICCT, 2018). Consequently, all costs related to the trailer will be multiplied by 1.4, including the costs for energy efficiency improving technologies.

4.2.9 *Results*

Figure 12 shows the breakdown of the pre-tax retail price in 2020, 2030 and 2040 for the articulated long haul truck (the breakdowns for the other truck configurations are included in Appendix F). The main differences over time are the decrease of the battery and fuel cell costs (included in the drivetrain bar). Since the mark-up factor is a percentage of the total vehicle costs, which changes considerably over time, the absolute mark-up decreases significantly for zero-emission trucks.

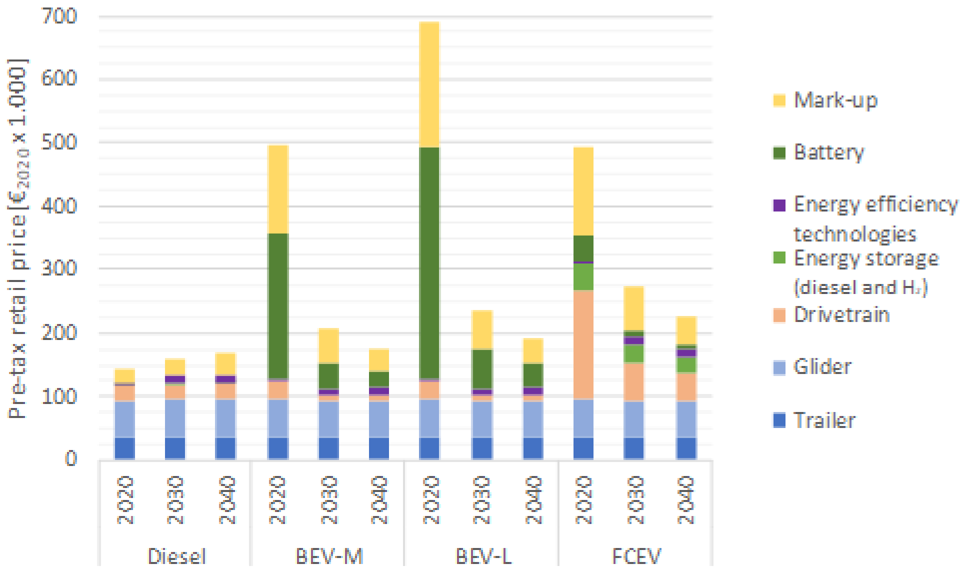

Figure 12: Pre-tax retail price breakdown for the articulated long haul truck including trailer.

An overview of the derived pre-tax retail prices for 2020, 2030 and 2040 of the trucks in this report is presented in Table 14.

Table 14: Vehicle pre-tax retail price including mark-up factor and trailer [$€_{2020}$].

Configuration	Drivetrain	2020	2030	2040
Rigid urban	Diesel	79,000	87,000	92,000
	BEV medium	147,000	88,000	80,000
	BEV large	159,000	91,000	81,000
Articulated regional	Diesel	144,000	159,000	170,000
	BEV medium	355,000	183,000	162,000
	BEV large	413,000	193,000	167,000
Articulated long haul	Diesel	144,000	159,000	170,000
	BEV medium	498,000	207,000	176,000
	BEV large	690,000	236,000	193,000
	FCEV	494,000	274,000	226,000
Articulated construction	Diesel	144,000	159,000	170,000
	BEV medium	295,000	175,000	157,000
	BEV large	393,000	192,000	166,000
	FCEV	459,000	252,000	208,000

4.3 Energy prices

As the uptake potential is determined at a country-specific level, end-user energy prices are also determined for every EU member state and the UK. In this section the energy prices averaged for the whole of the EU+UK are presented (energy prices per country can be found in Appendix G).

4.3.1 Diesel

The conventional diesel price strongly correlates with the crude oil price.
The 10-year average oil price in 2020 was 70 € per barrel. Projections up to 2023 are obtained from the July 2022 EIA short-term energy outlook (EIA, 2022), which includes the effect of the war in Ukraine. The oil price projections from 2030 onwards were taken from the World Energy Outlook 2021 (IEA, 2021). This includes two scenarios known as 'stated policies'[9] and 'announced pledges'[10]. The central scenario in this report is based on the 'stated policies' scenario. The oil prices between 2023 and 2030 are linearly interpolated.

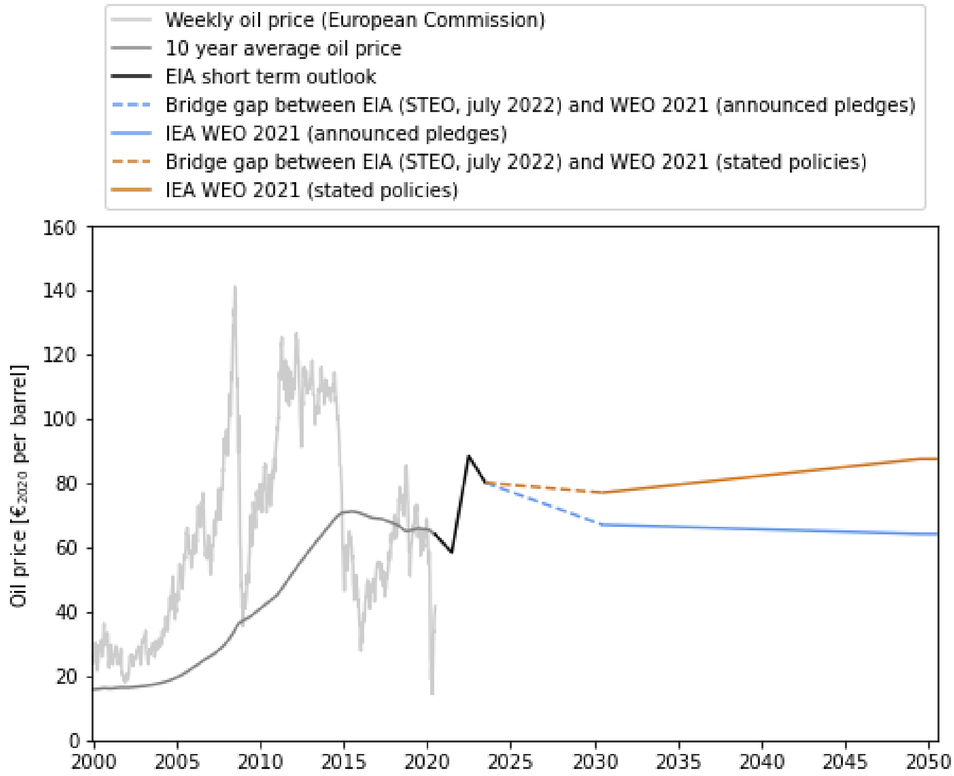

Figure 13: Oil price projections.

The crack spread[11] between crude oil and diesel (excluding taxes and levies) is based on the 10-year average values of both in 2020, which is 9.1 € per barrel or 7.6 eurocents per litre. Based on this crack spread and the current excise duty rates in EU countries, the diesel price projections are derived from the oil price projections. Projections for the EU+UK average diesel price (including excise duty and excluding VAT) are shown in Figure 14. For the calculations at country level, crack spreads and diesel price projections are determined in the same way. The country-specific results and projections can be found in Table 38 in Appendix G.

[9] The Stated Policies Scenario does not just take account of existing policies and measures but also of those that are under development.
[10] In the Announced Pledges, countries fully implement their national targets to 2030 and 2050, and the outlook for exporters of fossil fuels and low emissions fuels like hydrogen is shaped by what full implementation means for global demand.
[11] Crack spread measures the difference between the purchase price of crude oil and the selling price of finished products, such as gasoline and distillate fuel, that a refinery produces from the crude oil.

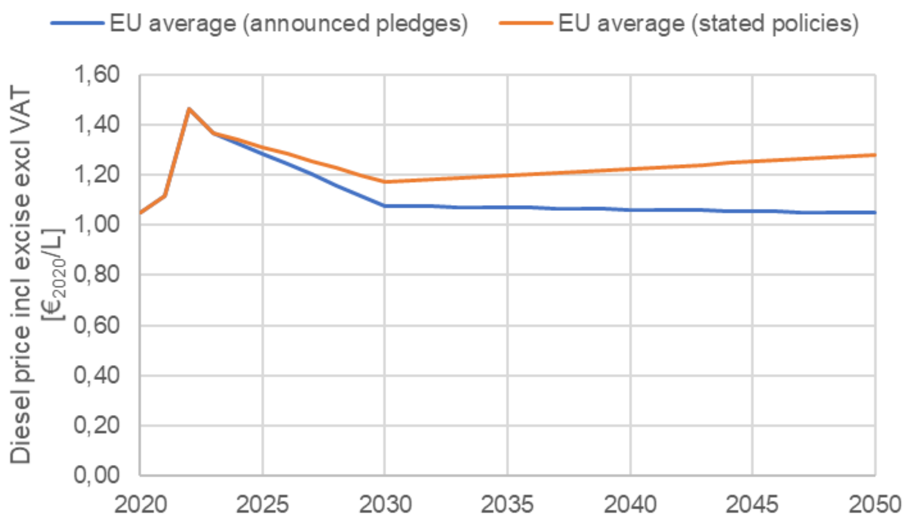

Figure 14: EU+UK average diesel price projections.

4.3.2 *Electricity*

The electricity price as presented here consists of three elements: the production cost, the distribution cost and the cost of charging infrastructure. The 2020 electricity prices are based on the 10-year average prices per member state and for the EU+UK average, a similar approach as used for the diesel price. These prices are obtained from Eurostat. The selected consumption band is 'IC' for non-households which is for companies with an annual electricity consumption between 500 MWh and 2,000 MWh. As a reference, this corresponds to a logistics company with a fleet of 5 to 18 electric trucks driving 350 km/day for 265 days/year.

The consumption for fast charging stations for trucks is likely to be in a higher consumption band, resulting in a lower electricity price. As an indication, for the ID consumption band electricity prices could be approximately 12% lower. In order not to underestimate electricity prices, the IC band is assumed for charging stations, having the same electricity production and distribution cost as for depot charging.

The projection of the electricity price beyond 2020 is based on relative changes according to the EU reference scenario 2020[12]. This results in an EU+UK average price increase of 6% between 2020 and 2050. Due to the variations in the projected electricity price development per country, the relative price differences between countries varies significantly.

4.3.2.1 *Depot charging infrastructure cost*

When charging at a depot, the recharging equipment cost must also be accounted for. The costs for depot charging equipment and the grid connection are assumed to be 0.047 €/kWh, based on (Kippelt & Burges, 2022). The overall resulting EU+UK electricity price for end users is depicted in Figure 15.

[12] The development of the electricity price in the EU Reference Scenario 2020 includes the effects of the EU ETS based on the revision of the EU ETS Directive in 2018.

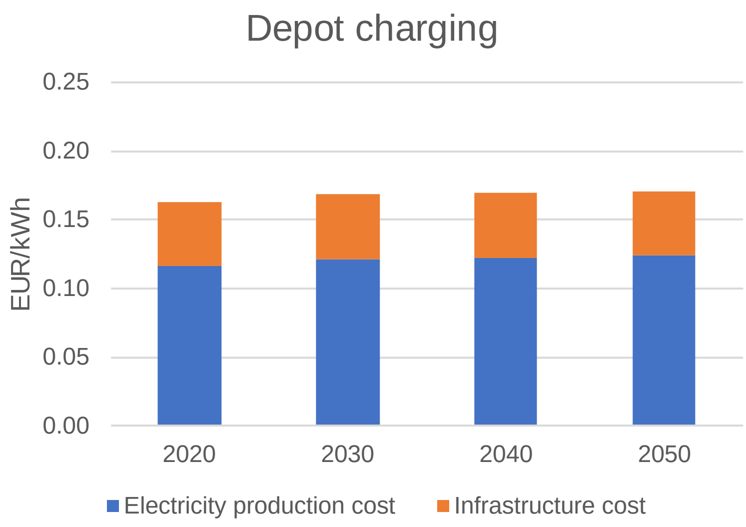

Figure 15: Assumed development of the EU+UK average end user electricity price when charging at the depot.

4.3.2.2 *Fast charging infrastructure cost*

Fast charging requires a different type of equipment, resulting in higher costs compared to depot charging. Based on (Kippelt & Burges, 2022), the costs for fast charging equipment and grid connection are 0.073 €/kWh in 2020, 0.096 €/kWh in 2030 and 0.055 €/kWh from 2040 onwards. Moreover, to account for profit margins and other potential costs, a mark-up factor of 10% is assumed on top of the charging equipment and grid connection cost.

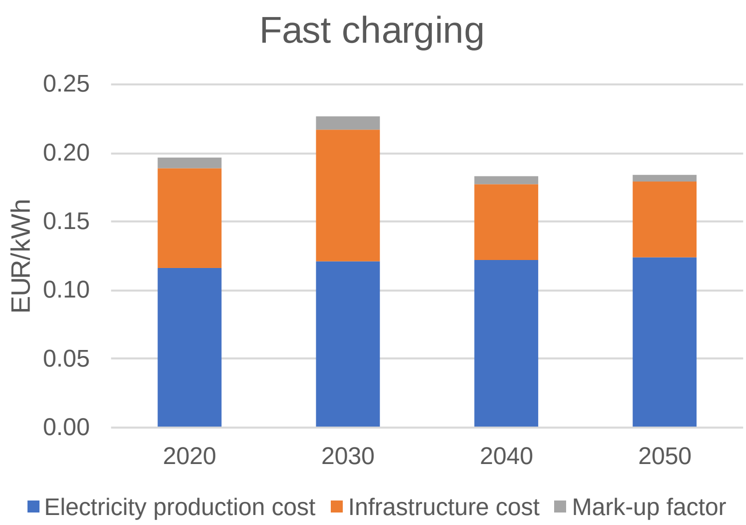

Figure 16:Assumed development of the EU+UK average end user electricity price when fast charging.

4.3.2.3 Overall electricity prices

Due to the lower cost and higher suitability with operations, depot charging (overnight) will be the favourable option for end users. However, battery-electric trucks will also require opportunity fast charging when the battery capacity is not sufficient to cover the daily trip distance. The extent to which this is required depends strongly on the deployment of the vehicles. On more demanding days, with longer distances, higher payload or more uphill driving, higher shares of opportunity charging will be required. To a lesser extent, also high or low ambient temperatures may result in a higher demand for opportunity charging. It is assumed that electric trucks will be able to charge one full battery (in most cases overnight) at the depot. Any distance beyond the range of one full battery, is assumed to be charged at a fast-charging station during the legally required 45 minutes rest break.

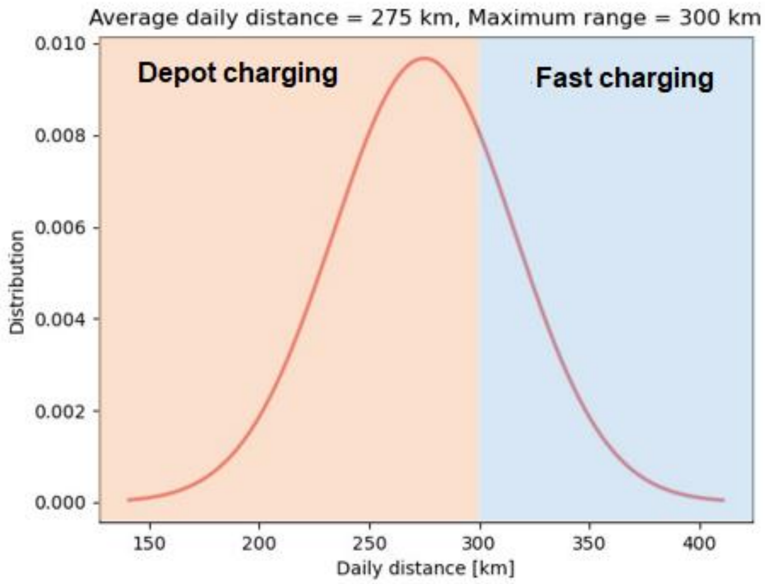

Figure 17: Example of the variation in day-to-day trip kilometres for a vehicle with an average daily mileage of 275 km.

For example, if a fully charged battery provides a range of 300 km, the depot charging price is used for the share of days with trips below 300 km. For the share of days with higher distances, the depot charging price is used for the first 300 km, and the fast-charging price is applied for the distance driven beyond 300 km.

Finally, these results are combined to determine a weighted average electricity price. Figure 18 shows an example of the relation between the aggregated electricity price and the daily distance increases. A larger battery results in a lower average electricity price, since more electricity can be charged at the depot and the vehicle is less reliant on fast chargers. On the other hand, a larger battery also means a higher vehicle price.

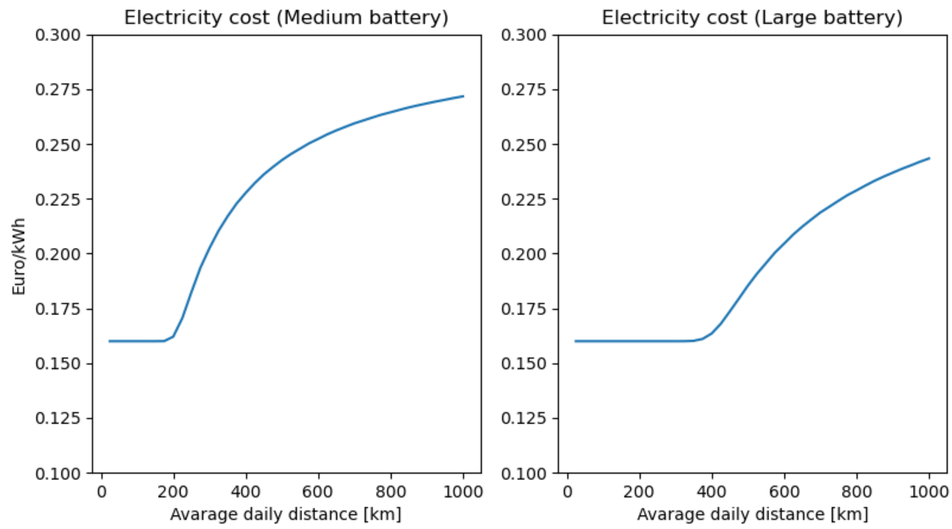

Figure 18: Example figure for the progressive electricity price as average daily distance increases.

Note that in practice, a driver would likely use a public fast charger before the battery is empty and would charge more electricity than strictly necessary to avoid the risk that the battery is depleted before the depot has been reached.

4.3.3 Renewable hydrogen

It is assumed for this analysis that only renewable hydrogen will be supplied to FCEVs in Europe. If the renewable hydrogen is to be produced outside of Europe due to lower renewable electricity costs, it would need to be compressed and transported through an inter-continental transmission pipeline network or liquefied and transported via cryogenic tanker vessel which would entail considerable additional energy conversion losses. Other overseas transport options include ammonia or liquid organic hydrogen carriers (LOHCs) which would be easier to transport but would lead to even higher conversion losses.

Unless a comprehensive domestic distribution pipeline network is made available in the mid-term future, the domestic distribution from the production site or the import terminal (such as a sea port) to the refuelling station would need to be handled by inefficient liquefied hydrogen tanker trucks. A more promising option until at least the 2030s seems to be the decentralised production of renewable hydrogen at a location next to the refuelling station from dedicated renewable electricity supplied through a power purchase agreement (PPA).

The latter option is therefore used to quantify the end-user renewable hydrogen price for this analysis. This assumption is further supported by the fact that a continuous hydrogen pipeline network would not emerge before 2040 according to the plans of the European gas industry (Guidehouse, 2022).

Country-specific renewable hydrogen prices and refuelling infrastructure costs are obtained from (ICCT, 2022). Hydrogen itself currently not taxed, the electricity used to produce the hydrogen is. Additionally, a mark-up factor of 10% for the refuelling station cost are added to account for profits and other cost of the station operator. The EU average prices are depicted in Figure 19 while the country-specific data can be found in Appendix G.

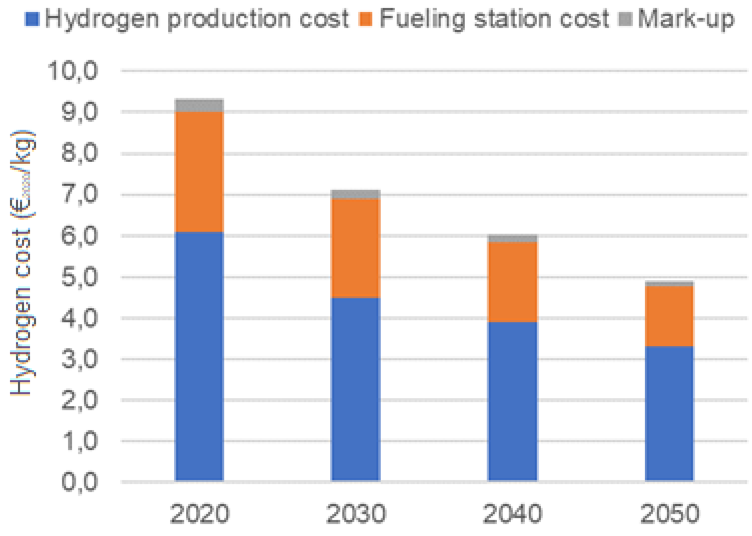

Figure 19: Assumed development of the EU+UK average end user renewable hydrogen price based on local production.

4.3.4 *Mileage split per country*

The long haul trucks will cross different countries during some of their trips which will impact the energy price. An estimate of the cross-border vehicle mileages is used to calculate final energy prices (mileage split shown in Table 35 in Appendix **D**). For the truck configurations other than long haul it is assumed that the trips are driven 100% in the same country as where the vehicle is registered.

4.4 Maintenance costs

The maintenance costs for the diesel truck and the BEV are based on (ICCT, 2021). For the maintenance cost of the FCEV the average between diesel and BEV is assumed for this report. No distinction is made for the different vehicle types.

Table 15: Assumed maintenance costs, based on (ICCT, 2021).

Drivetrain	**Cost [€/100km]**
Diesel	18.50
BEV	13.24
FCEV	15.87

4.5 TCO results

Per country the TCO is determined for every vehicle configuration, for every year between 2020 and 2040, and for a range of daily distances specific for that country, using the country-specific energy prices. The net present value (NPV) is determined over a first use period of five years and expressed in euros per kilometre.

The TCO results shown in this section are based on EU+UK average energy prices and are included for illustrative purposes. The overall techno-economic uptake potential within the EU+UK, which will be discussed in section 6, is based on the country-specific TCO calculations.

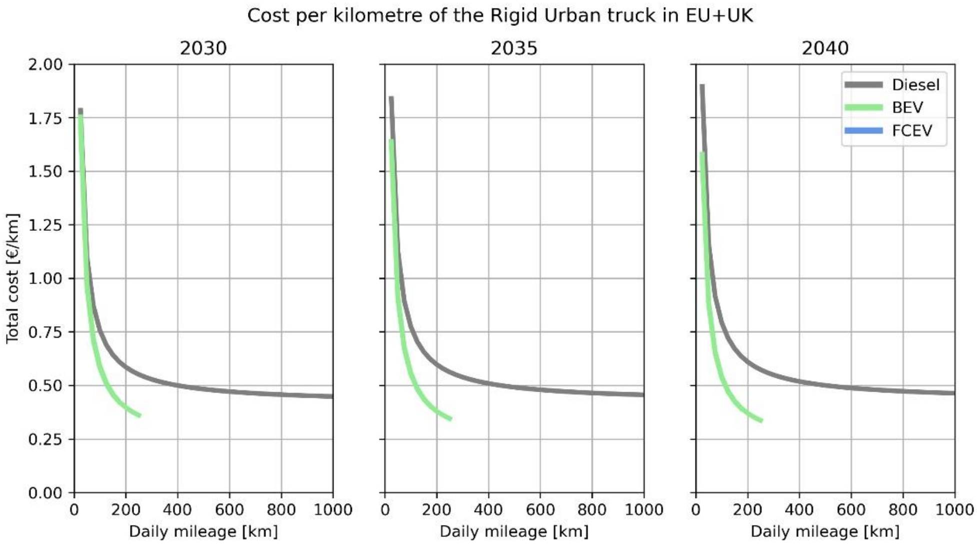

Figure 20: Cost per kilometre of the rigid urban delivery truck using EU+UK average energy prices (two green lines indicate BEVs with two different battery sizes).

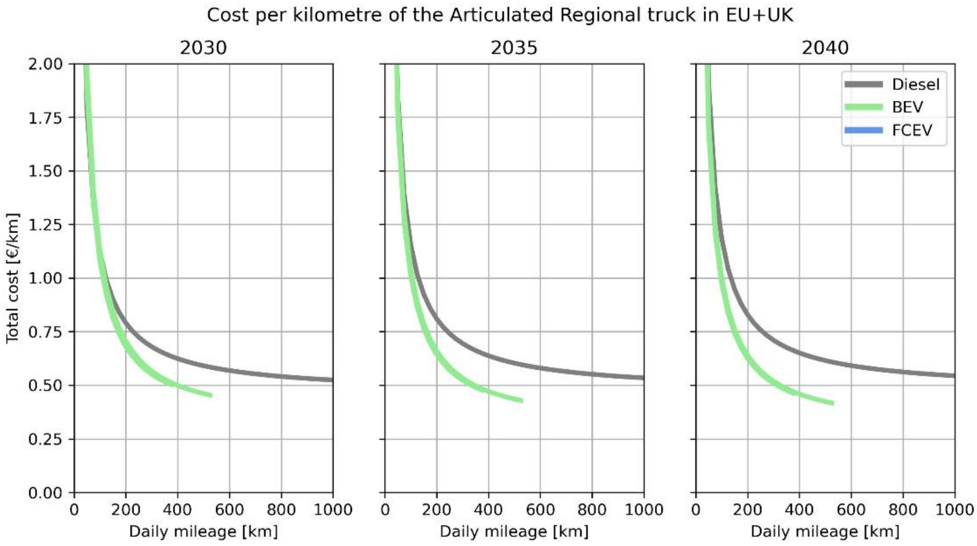

Figure 21: Cost per kilometre of the regional delivery truck using EU+UK average energy prices (two green lines indicate BEVs with two different battery sizes).

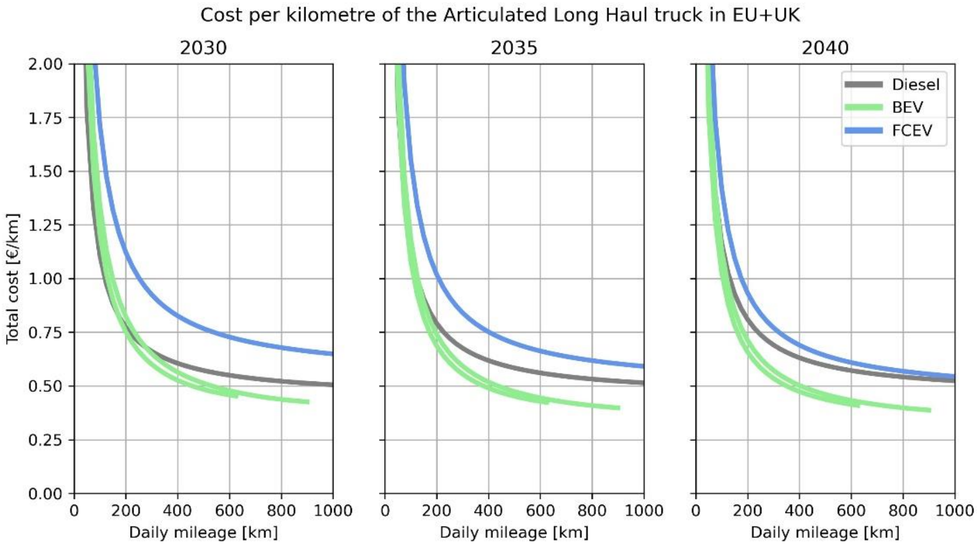

Figure 22: Cost per kilometre of the long haul truck using EU+UK average energy prices (two green lines indicate BEVs with two different battery sizes).

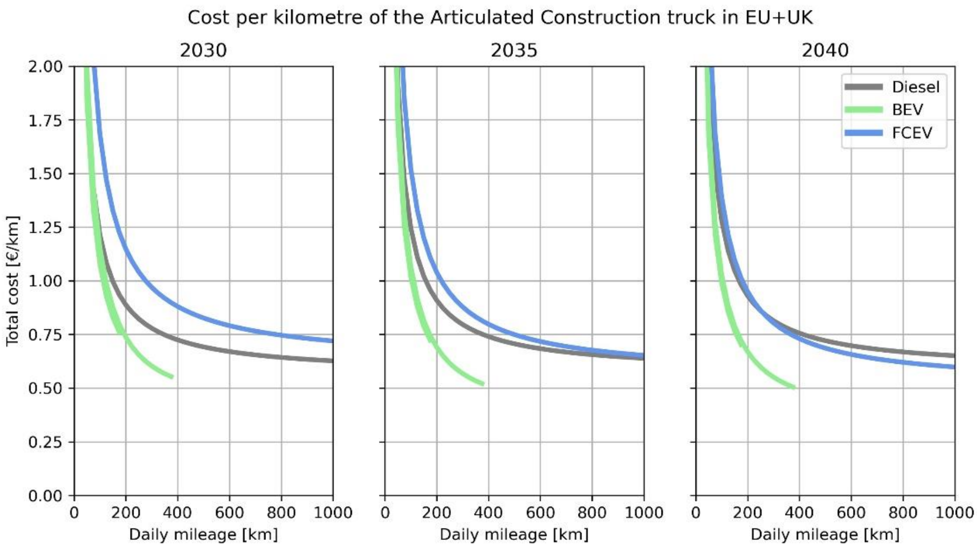

Figure 23: Cost per kilometre of the construction truck using EU+UK average energy prices (two green lines indicate BEVs with two different battery sizes).

In Figure 20 to Figure 23 the TCO's of the four truck segments are presented based on EU+UK average energy prices. Higher mileages result in a lower average cost per kilometre as the initial vehicle investment cost is written off over a longer distance. The TCO of BEVs has only been determined up to the maximum daily range that they can cover. It is assumed that the daily range of BEVs is limited to one full battery charge plus 45 minutes of charging at a charging rate of 1 C with a maximum of 500 kW. This is explained in more detail in section 5.5.

It can be concluded that from 2030 onwards BEV trucks are the most cost-competitive option except for a small share of vehicles at very low daily distances. This lower cost is mainly driven by continued reductions in battery costs and increasing energy efficiency. This is the case for all vehicle types assessed, even at low mileages.

For the EU+UK average situation, the TCO of the FCEV long haul articulated truck and articulated construction truck in 2030 is significantly higher than that of their diesel equivalents. Although getting closer in 2035, they are still more expensive, except for extremely high mileages for the construction trucks (>1000 km/day on average). Towards 2040, the TCO of the FCEV articulated construction truck becomes cost competitive but only at average daily mileages beyond 300 km. The FCEV long haul articulated truck only becomes cost competitive in 2040 for very high mileages (>1000 km/day). Such distances can only be achieved by two drivers in one vehicle.

As mentioned above, these figures are based on EU+UK average energy prices. Since energy prices vary per country, so does the cost competitiveness of the various drivetrain types. These conclusions are therefore not applicable all throughout the EU+UK.

5 Range requirements

As shown in section 4.5, the TCO difference between the various drivetrains depends on the distance that vehicles drive. Vehicles with lower energy costs such as battery electric trucks benefit from higher daily distances but may be faced with range limitations. Therefore, this section focuses on the range requirements of the use cases and the applicability of the vehicles.

5.1 Average mileage per country and region

Trucks are deployed differently in the examined countries. This is one of the reasons that the TCO can vary between countries. The average annual distance per country for the different vehicle categories as used in this analysis is based on information provided by the ICCT (ICCT, 2022). In Appendix D the assumed average annual vehicle distance per country can be found.

5.2 Mileage distribution of the fleet

Within the observed countries, trucks are also deployed differently. Some vehicle types drive more than others, and also within each category there is a large spread in mileages between vehicles. In the Netherlands, for example, the distribution of annual distances over the truck fleet is well known by data provided by the Dutch road authority (RDW). Figure 24 shows the average daily distance distribution of the rigid truck fleet and articulated trucks fleet in the Dutch context. This is based on the monitored annual distance of the vast majority of the Dutch truck fleet and divided by 265 working days.

Based on the data from the Netherlands, the standard deviation around the mean is determined. Since there is a lack of consistent data for other European countries, it is an equal (absolute) standard deviation is applied to all the European countries. The standard deviation based on the Dutch data is 146 km for articulated trucks and 118 km for rigid trucks. This standard deviation corresponds well to what was observed for Germany in (Wentzel, 2020).

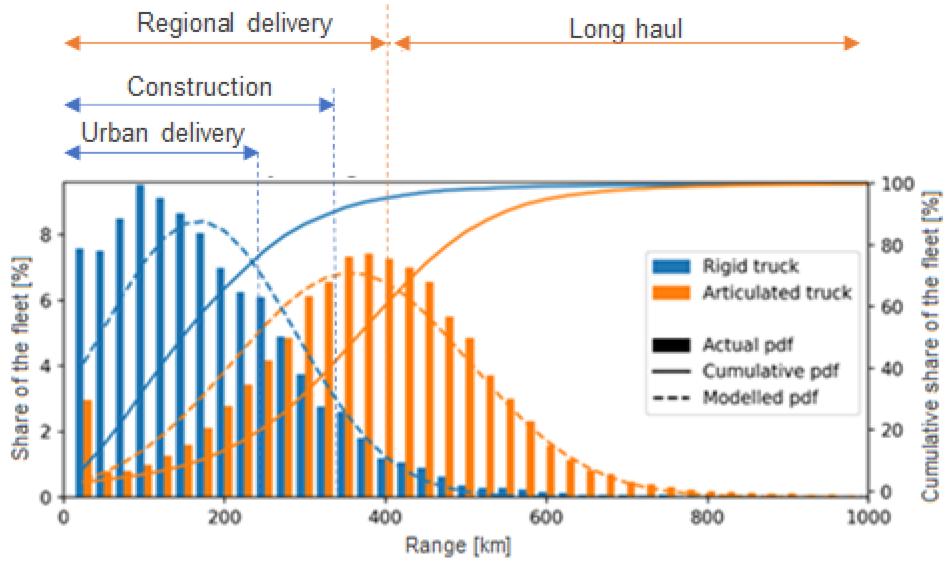

Figure 24: Actual vehicle deployment data in the Netherlands in comparison to normalized modelled normal distribution approach.

The average annual distance for various vehicle category fleets as provided by the ICCT (ICCT, 2022) shows higher average daily distances of articulated trucks for the Netherlands than the data source for the Netherlands itself, provided by RDW. In order to assess the effect of lower daily average distances, a sensitivity analysis is performed, which is discussed in section I.3.1.

The annual average daily distance of rigid trucks goes up to approximately 600 km/day. Urban delivery rigid trucks are assumed to drive not more than 250 km/day on average (see Figure 24). Therefore, rigid trucks with annual average distances higher than 250 km/day are assumed not to be urban delivery trucks and are out of scope. The rigid trucks are dimensioned for these types of deployment, especially the rigid battery electric trucks driving more than 250 km/day would probably be fitted with larger battery packs than assumed here.

Regional delivery articulated trucks typically drive lower distances than long haul articulated trucks. Therefore, it is assumed that daily average distances lower than 400 km per day are typically driven by regional delivery trucks, while the higher distances are driven by long haul trucks. Based on these assumptions, over 80% of articulated trucks (EU+UK average) have an average daily mileage over 400 kilometres per day and are therefore assumed to be long haul trucks (see Figure 24).

As no specific average mileage distribution is available for construction trucks, it is assumed that this equal to the annual average distance distribution of rigid trucks. The annual average daily distance of rigid trucks goes up to 600 km/day. It is assumed that construction trucks do not drive more than 350 km/day on average (see Figure 24). The distribution of rigid trucks is therefore cut off at an annual average daily distance of 350 km/day.

5.3 Annual mileage variations as a function of age

Generally, annual distances reduce with vehicle age. To include this effect, the annual distance driven by a vehicle is indexed based on a correction factor. The correction factors which are used in this report are given in Table 16 and are based on the TRACCS database. The average of the correction factors over 5 years is 1.

Table 16: Variation of the average annual mileages as a function of vehicle age. These relative correction factors are applied to vary the average annual mileage.

Year	1	2	3	4	5
Distance correction	1.139	1.065	0.995	0.931	0.870

5.4 Daily distance variation

The distance travelled by individual trucks also varies from day to day. The variation of daily mileages is based on real world data of a Dutch logistics company which contains the day-to-day use of a fleet of heavy-duty trucks with various types of deployment (TNO, 2022). The results were discussed and verified in stakeholder consultations held for this analysis, leading to the conclusion that they can be considered representative for the whole of the EU.

As can be seen in Figure 25, the relative standard deviation decreases for increasing average daily mileages. This means that the standard deviation is lower for vehicles with a higher average daily mileage. This is due to the upper boundary of about 720 km/day for one driver (the daily mileage can increase up to a theoretical maximum of 1600 km/day with two drivers, but that is only for a small share of the fleet). Due to this boundary, a vehicle with a high average distance, say 700 km/day, could not afford many days with a low mileage as it would simply not reach the high average daily mileage. Similarly, the lower boundary of 0 km/day has a lower standard deviation because days with a high mileage would raise the average daily mileage.

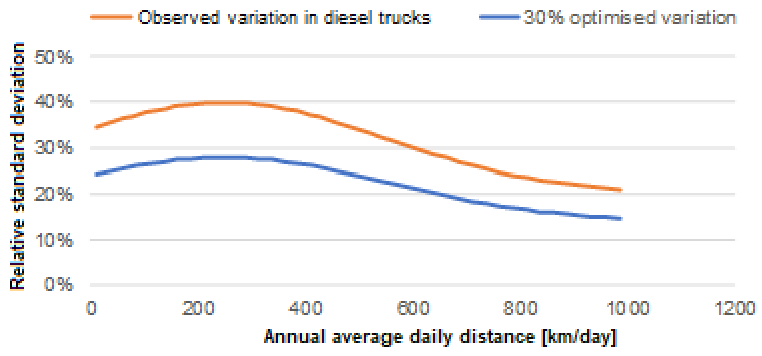

Figure 25 Variation of day-to-day mileages relative to the average daily mileage. With an optimization factor of 0% (orange) and an optimization factor of 30% (blue).

The same standard deviation for daily distance variations is applied to all countries. It should be noted however that this standard deviation is based on diesel vehicles. Since those are not range-limited, all the vehicles are interchangeable and deployable on any given trip. In the absence of any range constraints, there is no incentive for fleet operators to limit this variation and optimise the fleet deployment depending on the range limitations.

However, for BEVs this incentive does exist. Driving less distance than the battery capacity would require the vehicle's battery to be oversized and would therefore result in higher cost. On the other hand, an undersized battery means that more opportunity charging would be required, potentially resulting in less vehicle uptime and higher costs. Especially if a fleet operator has BEVs with different battery capacities, optimization would likely take place to select the truck best fit for a certain trip length. This will yield a smaller variation. To account for this, it is therefore assumed that the standard deviation can be reduced by 30%. A sensitivity analysis of this assumption with a lower reduction is included in section 6.3.

5.5 Resulting applicability of battery electric trucks

As explained in section 5.4, the daily mileage variation is a relevant parameter, especially for BEVs as they can have a more limited daily range. The rules on driving times and rest periods[13] foresee maximum daily driving periods of 9 hours, minimum rest periods of 11 hours overnight and breaks of 45 minutes after four and a half hours of driving. These time windows provide the opportunity to recharge and refuel ZEVs without causing vehicle downtime.

It is therefore assumed that the maximum daily range of battery electric trucks is based on the energy obtained by one fully charged battery plus 45 minutes of opportunity charging at a C-rate of 1 C with a maximum of 500 kW. Thus, vehicles with a larger battery are assumed to fast charge at higher power levels than BEVs with a smaller battery. Even though it is expected that over time chargers will become commercially available with power levels of 1 MW or even higher, the charging power in this study is assumed not to exceed 500 kW. This value is used because likely not all fast chargers will be able to charge at these power levels or active charging management leads to reduction in real charging power. Moreover, the charging power decreases with an increasing state of charge. Therefore the average charging power during (partial) recharging a battery is lower than the maximum power available from the charger.

As explained in section 5.4, vehicles are used differently from day to day. If the share of days, at which the distance to be covered is larger than the maximum daily range of a BEV (one full battery charge plus 45 minutes of fast charging) is more than 10%, it is assumed that battery electric drivetrains are not suited to replace the diesel truck. It is assumed that the remaining 10% of days can be covered by diesel trucks as long as they are still in the fleet. If later on diesel trucks would not be sufficiently available in the fleet, logistics plannings would need to be adjusted to either have trucks with larger batteries available for such driving days, to split activities between multiple trucks or to shift to other modes of transport.

In Figure 26 this cut-off point is shown for an average daily mileage of 300 km, where the blue area below the curve accounts for 90% of the daily trips.

[13] Regulation (EC) No 561/2006 and amendments

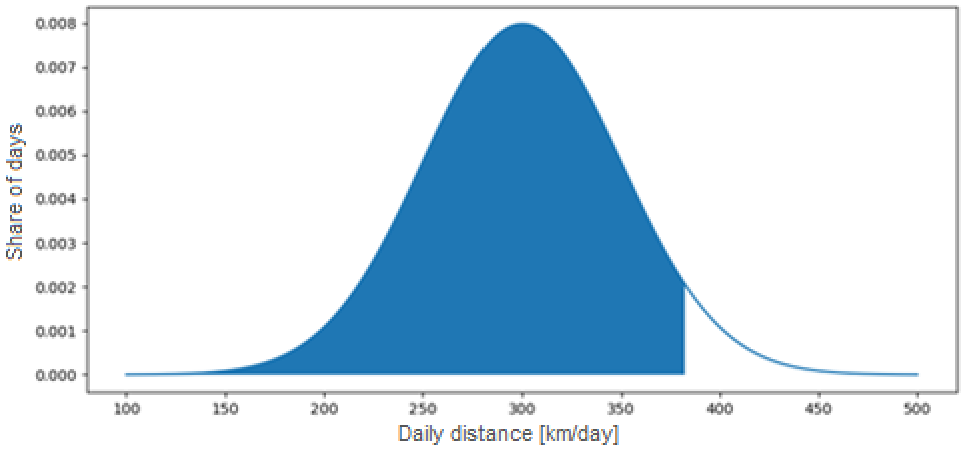

Figure 26: Cut-off point example for a range bin of 300 km.

Even if a vehicle's average daily distance is lower than the maximum daily range of a BEV, on some days the driven distance will still exceed the maximum range. For instance, a vehicle with an average daily mileage of 400 km drives 535 km or more on 10% of days. Therefore, it is assumed that a BEV with a maximum daily range (including 45 minutes of fast charging) of 535 km is required to replace a diesel truck that covers 400 km per day on average. If it is assumed that 95% of the days should be within the maximum BEV daily range (including fast charging) instead of 90%, the BEV's daily range should at least be 573 km instead of 535 km. Table 17 shows the required daily range of BEVs (including fast charging) required for various average daily distances.

Table 17: Examples of the minimum range (based on one full battery charge plus 45 minutes of fast charging) required to perform 90% or 95% of the daily distances for a certain average daily distance.

Daily average distance [km/day]	**Required BEV daily range [km] (including 45 min. fast charging)**	
	90% of days	**95% of days**
200	271	291
400	535	573
800	976	1026

In the central scenario, presented in this report, it is assumed that a BEV can replace a diesel truck if it can drive the daily distance for 90% of the days. A scenario with a value of 95% of the days is further assessed in the sensitivity analysis (in section I.3.2).

6 Market-driven uptake scenario

In this section the results for the techno-economic market uptake potential of ZEVs are presented. This market uptake potential is the potential share of the new ZEV sales that the market could achieve on its own, based the share of the fleet for which ZE trucks can replace diesel trucks in terms of deployment and ZE trucks have lower TCO than diesel vehicles. As explained in section 1.5, this uptake potential likely differ from the actual uptake of ZE trucks since the decisions of end-users depend on more factors than cost and applicability, e.g. supply of vehicles, availability of refuelling and charging infrastructure. It is based on existing policies only, the effects of possible new policies are further assessed in the next section.

The potential market shares are modelled separately for each vehicle category and for of the EU and the UK. Moreover the uptake potentials and aggregated to seven regions and to an overall EU+UK level.[14] Every step described in this section is modelled separately for each of the four truck segments.

6.1 Methodology

6.1.1 Affordability and applicability

As explained briefly in section 1.5, the techno-economic uptake potential is based on TCO competitiveness and applicability of zero-emission drivetrains. For every average daily distance, the TCO of the three drivetrains is compared for the various vehicle types and for every year between 2020 and 2040. The drivetrain with the lowest TCO is selected for vehicles which drive that average daily distance. For BEVs, the additional requirement is that their maximum daily range (based on overnight charge plus 45 minutes of fast charging) is sufficient to cover 90% of the daily distances associated with the distance distribution underlying that specific average daily distance (as explained in section 5.5).

At least for some years to come, the upfront vehicle costs of BEVs and FCEVs will be higher than those of equivalent diesel vehicles. However, the energy and maintenance costs of BEVs are lower from 2020 onwards. Thus, the higher the distance driven, the greater the economic benefit for BEVs. For FCEVs this is also the case but only from about 2030 onwards. As shown in section 4.5, beyond a certain mileage the TCO of BEVs or FCEVs becomes lower than that of diesel vehicles. In the example shown in Figure 27, this cost parity point is illustrated by the blue vertical line. For any vehicle with a mileage higher than this line, the TCO of a battery electric vehicle is lower than that of an equivalent diesel vehicle.

As explained in section 5.5, beyond a certain average daily distance, it is assumed that BEVs are no longer applicable due to range limitations. This is indicated in Figure 27 by the vertical orange line. Therefore, in a given year, any vehicles sold that will have a daily mileage between the vertical blue and orange lines are assumed to be best suited for a battery electric drivetrain. In the example shown in

[14] To illustrate intermediate results, a 29th model run has been executed where average energy prices and vehicle distributions for Europe are used. This provides a fictional representation for an average situation in Europe. The final aggregated results for Europe do not follow from this average input scenario, which is portrayed in this section, but are the result from a bottom-up analysis for each individual country.

Figure 27, 85% of vehicles have a daily mileage which is high enough to result in a TCO lower than that of a diesel truck and low enough for BEVs to be applicable. Over time, this share will increase as the upfront vehicle costs of ZEVs decrease, thereby lowering the daily mileage beyond which ZEVs become cost competitive. In Figure 27 this can be visualised by a movement of the blue line to the left.

The TCO is calculated for average daily mileages ranging between 0 km and 1000 km per day in mileage steps of 25 km. For each daily mileage step, the most cost-effective option is selected. This is done separately for each country, taking into account country specific cost factors. In order to derive the uptake for a specific region or EU+UK wide, per daily mileage step the results are aggregated using an average weighted based on the number of new vehicle sales in each country with that average daily mileage.

This calculation methodology is applied for:

- All four vehicle types included in this assessment (rigid urban delivery truck, articulated regional delivery truck, articulated long haul truck and articulated construction truck)
- every year between 2020-2040 to determine the uptake potential of zero-emission trucks
- all individual EU27 countries and the UK.

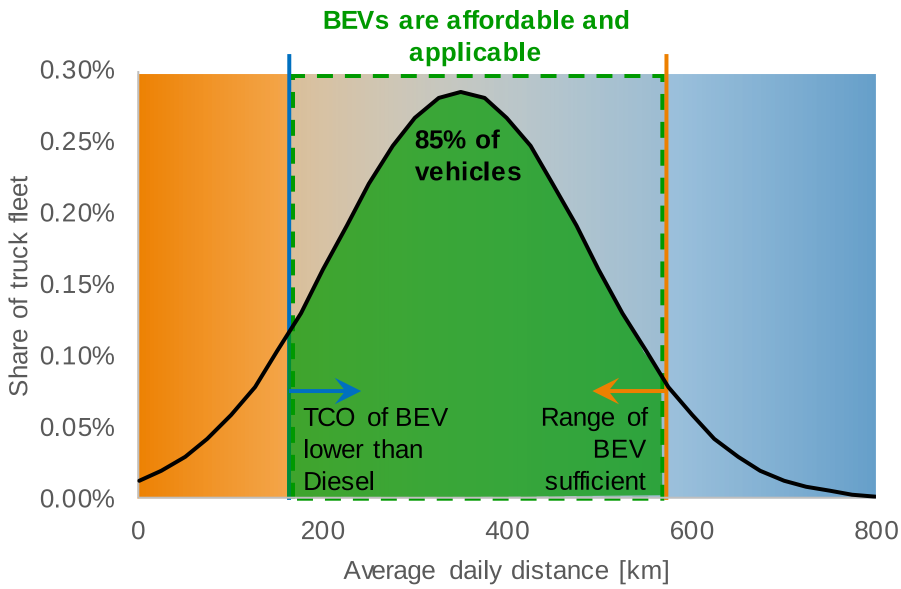

Figure 27: Illustrative mileage distribution of a truck fleet and the share of vehicles within a certain daily mileage range for which a BEV truck is the most affordable and applicable.

6.1.2 *Aggregation of country results*

As mentioned in the previous section, the energy prices and vehicle deployment are determined per individual country. The resulting market uptake potential per country is then aggregated to regions and to a European level using an average weighted by the number of new vehicle sales per country. The vehicle deployment is based on (ICCT, 2022) and country registration values are obtained from TRACCS (Emisia, 2013). The country-specific data can be found in Appendix D.

6.1.3 *Drivetrain selection*

The TCO is calculated individually for every vehicle segment, drivetrain, year and for an array of average daily distances (in bins of 25 km). For each combination of year and mileage bin it is determined which drivetrain has the lowest TCO (see section 5.5). If a BEV has the lowest TCO, it also has to fulfil the applicability criterion to be selected as the favourable drivetrain. This exercise is repeated for every individual country for and for every year between 2020 and 2040.

Combining these results with the distribution of average daily distances (see section 5.1) it can be determined which share of the fleet has ZEV uptake potential.

As an example, Figure 28 shows the uptake potential for the articulated regional delivery truck. The left part of the figure shows the favourable drivetrain type for every year and average daily distance bin. The right part of the figure shows the average daily mileage distribution. This shows that that BEVs become cost-competitive and applicable for vehicles that drive 275 or more kilometres per day on average from 2024 onwards. Moreover, these bins represent a relatively large part of the fleet in this segment (represented by the large blue bars on the right). Therefore they have a relatively large impact on the ZEV uptake potential. For average daily distances of 225 km, BEVs become cost-competitive in 2025. However, these only represent a relatively small share of the fleet and therefore only have a limited impact on the ZEV uptake potential.

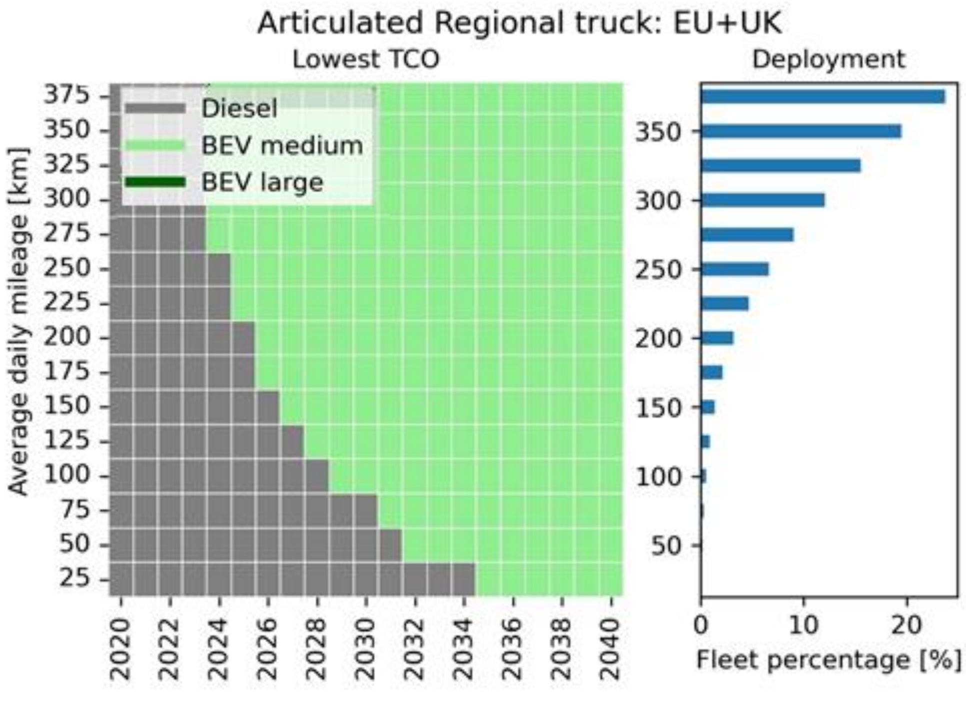

Figure 28: Example: Zero-emission uptake potential for articulated regional delivery trucks.

The analysis illustrated in this section is modelled for every country individually, after which the results are aggregated towards the EU+UK fleet. In the example depicted here the separate uptake potentials for the BEV configurations with medium and large battery are shown. In the following sections only the aggregated results are presented, for which the uptake potentials of the different BEV ranges are combined.

6.2 Aggregated results for the EU+UK and regions

The results of the model for the market-driven uptake potential are described in the sections below. Each of the four vehicle types is discussed separately. Uptake potentials are assessed for each individual country, however only the aggregated European results are presented here. The results per country can be found in Appendix H. Note that the final aggregated European result is an aggregation of the bottom-up computations for every country using country specific energy prices and deployments. This yields a result that is different from that of an higher-level assessment using overall EU+UK average energy prices and deployment distributions, and more accurate.

6.2.1 Uptake potential for urban delivery

Figure 29 shows the techno-economic uptake potential for ZE powertrains in rigid urban delivery trucks for the aggregated EU+UK. The battery electric vehicles are modelled with a maximum range of 150 km or 200 km on a single charge. When including 45 minutes of opportunity charging, the maximum range extends to 350 km per day. Given the daily variation (at least 90% of trips must be executable, see section 5.5) only trucks with an average mileage up to 250 km per day meet the criteria. The urban delivery trucks are capped at a maximum mileage of 250 km per day, meaning that beyond 250 per day the truck is no longer considered an urban delivery truck and must be dimensioned differently.

Beyond 2020, the prices of BEVs are assumed to come down significantly, resulting in TCO competitiveness also at lower mileages. On the upper end, the maximum range limits the uptake potential for vehicles with higher mileages. The maximum ZEV uptake potential of (100%) is already achieved by 2030.

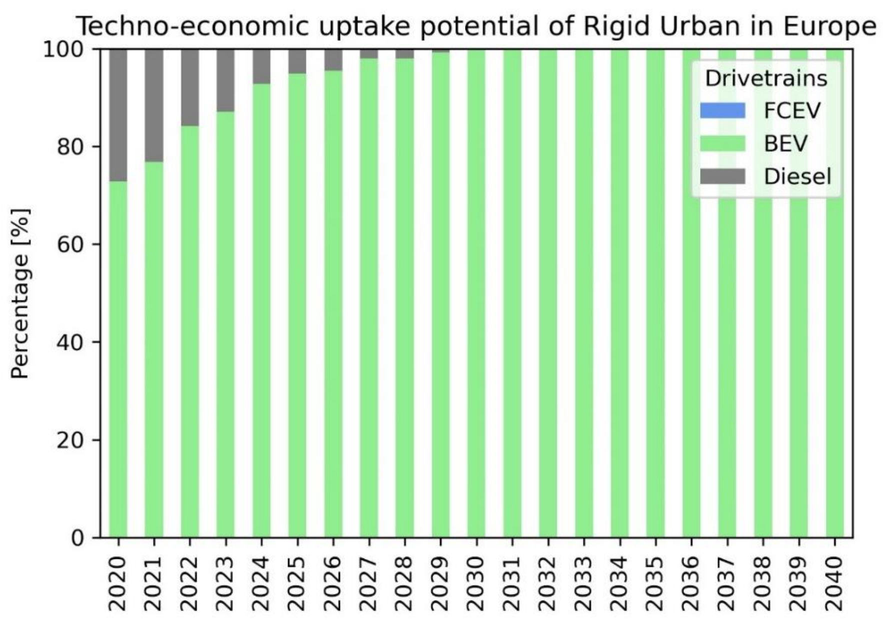

Figure 29: Aggregated techno-economic zero-emission powertrain uptake potential for rigid urban delivery trucks in the EU+UK.

6.2.2 *Uptake potential for regional delivery trucks and long haul trucks*

The difference between the articulated regional delivery and the articulated long haul truck lies only in the duty cycle, the battery capacities and the payload as their vehicle configurations are the same. The different duty cycles translate into a difference in energy consumption and therefore vehicle configuration and energy cost. The long haul truck is more likely to drive cross borders and therefore encounters various energy prices. This effect is accounted for according to the method described in section 4.3.4. The mileage distribution of articulated trucks has been described in section 5.2.

Figure 30 presents the results for the techno-economic uptake potential of ZEV for articulated regional delivery trucks. For 80% of the sales battery electric trucks would be cost competitive and applicable just before 2025, increasing to 100% by 2030. As the TCO of FCEVs is higher than that of BEVs and range of BEVs is sufficient to be deployed, there is no uptake potential for FCEVs.

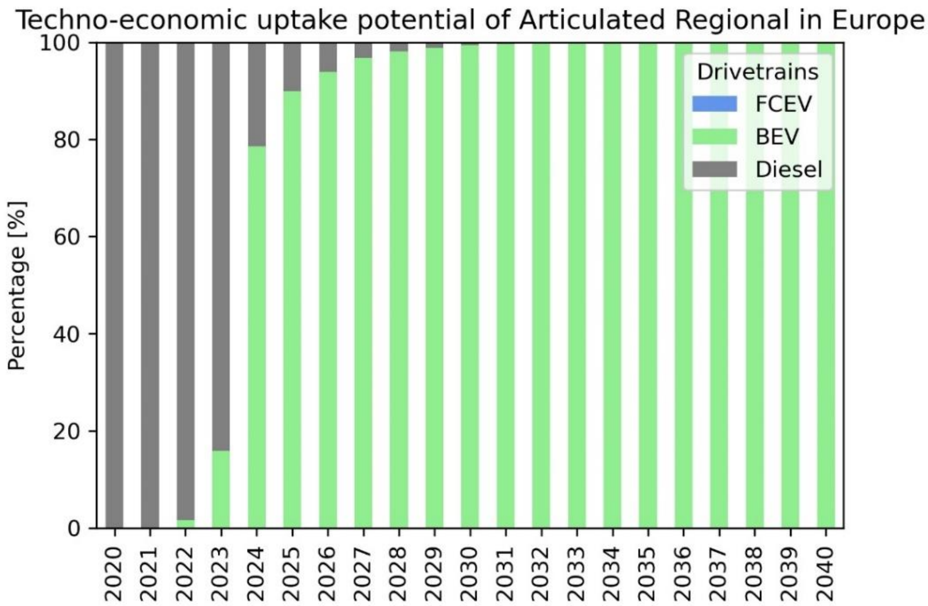

Figure 30: Aggregated techno-economic zero-emission powertrain uptake potential for articulated regional delivery trucks in the EU+UK.

As can be seen from Figure 31, the techno-economic uptake potential of ZEVs in long haul trucks is 80% by 2026, increasing to a maximum of close to 100% by 2031. Based on the assumptions in this report, the FCEVs have a higher TCO than diesel vehicles in the 2030s, even at high mileages, and do therefore not become cost competitive compared to equivalent diesel vehicles in the long haul segment with one exception. Only in Finland where hydrogen prices are expected to be relatively low and the average daily distances of long haul trucks is relatively high, FCEVs become the most cost competitive option for approximately 2% of the long haul truck fleet driving very high mileages.

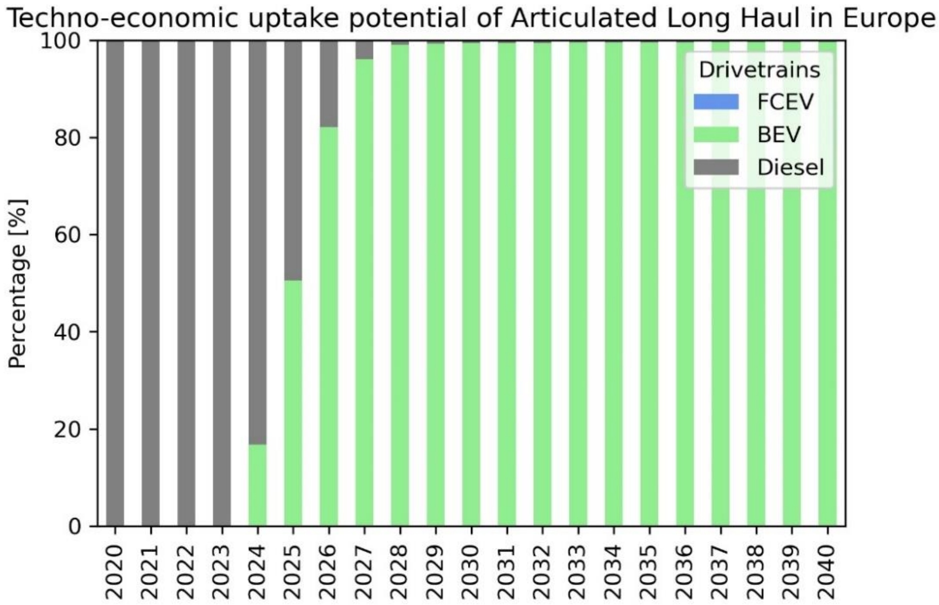

Figure 31: Aggregated techno-economic zero-emission powertrain uptake potential for articulated long haul trucks in the EU+UK

6.2.3 *Uptake potential for articulated construction trucks*

Figure 32 shows the share of vehicles for which zero-emission drivetrains become cost competitive and applicable for the articulated construction segment between 2020 and 2040. The techno-economic ZEV uptake potential of 100% is reached by 2033. Similarly as for the long haul truck, BEVs are the most cost competitive drivetrain type and have sufficient range (based on an overnight charge plus 45 minutes of fast charging per day) to cover the demanded distance. Since, BEV have lower TCO than FCEVs and BEVs have sufficient range to cover the deployment of construction trucks, there is no uptake potential for FCEVs under these conditions.

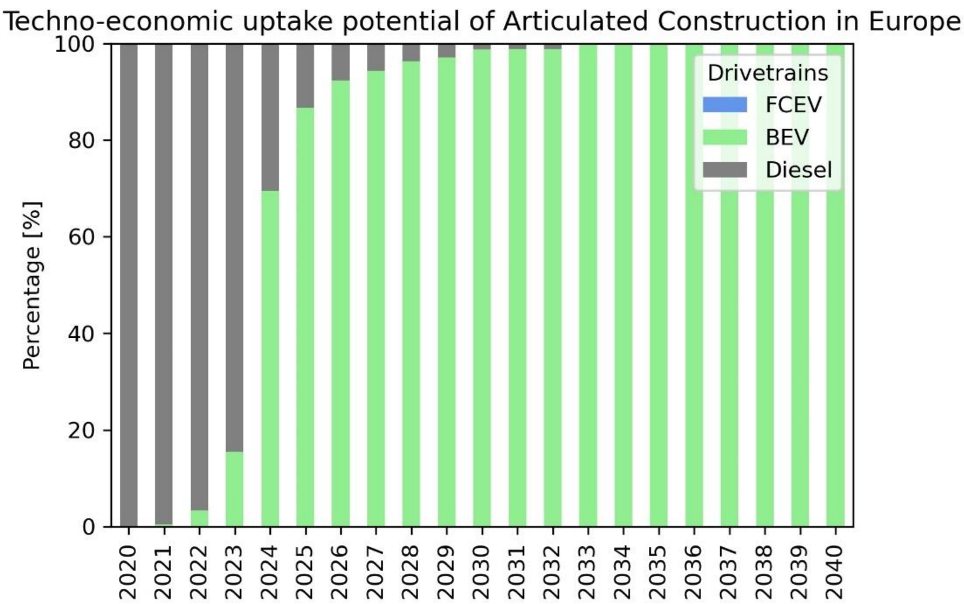

Figure 32: Aggregated techno-economic zero-emission powertrain uptake potential for articulated

construction trucks (with tipper) in the EU+UK.

6.2.4 *Uptake potential per region*

For the various European regions, the ZEV uptake potential is fairly similar and differences between regions are relatively small. This is particularly true for rigid urban delivery trucks, with BEVs reaching 100% uptake potential by 2030 in all seven regions. This is also the case for the articulated regional delivery trucks which reach 100% ZEV uptake potential in 2035 in all regions. For the articulated long haul trucks, differences are slightly larger especially in the earlier years. In Northern Europe close to 100% ZEV uptake potential of BEVs is already reached by 2025. In Southern Europe this takes until 2030.

Finally for the articulated construction trucks, the 100% uptake potential is reached the soonest in Northern Europe (i.e. 2032)followed by all other regions in 2033.

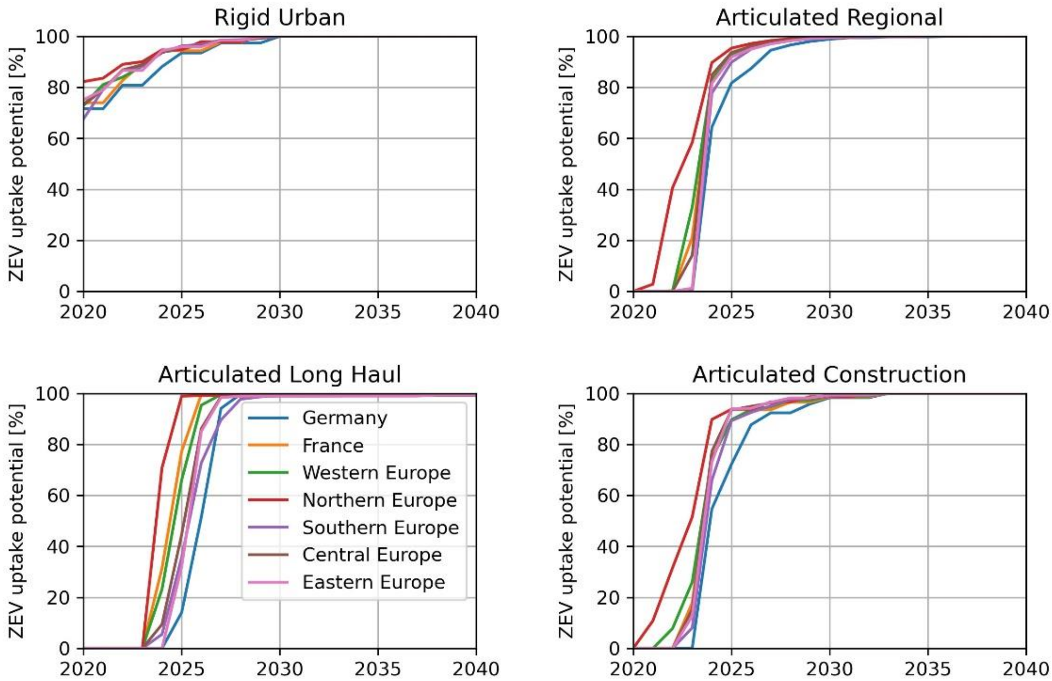

Figure 33: Techno-economic ZEV uptake potential between 2020 and 2040 within the seven distinguished regions for the four truck types assessed.

6.2.5 *Overall combined uptake potential*

The overall ZEV uptake potential of ZEVs in rigid urban trucks, articulated regional delivery trucks and articulated long haul trucks is shown in Figure 34. These three categories are weighted based on sales as taken from the TRACCS database that is also used to aggregate country specific results to regional results and EU+UK results (see section 6.1.2).

Figure 34 shows that the uptake potential of ZEVs increases to 99.6% by 2030, 99.8% by 2035 and 99.9% by 2040. Close to all of this potential is represented by BEVs as under the situation assumed in the central scenario these are always the more cost competitive drivetrain technology compared to FCEVs. As explained in section 6.2.2, in some countries in which a limited share of the truck fleet drives relatively large distances, BEVs cannot replace all diesel trucks due to range limitations while FCEVs are still not cost-competitive in those cases. However, this share is limited to 0.4% by 2030, 0.2% by 2035 and 0.1% by 2040.

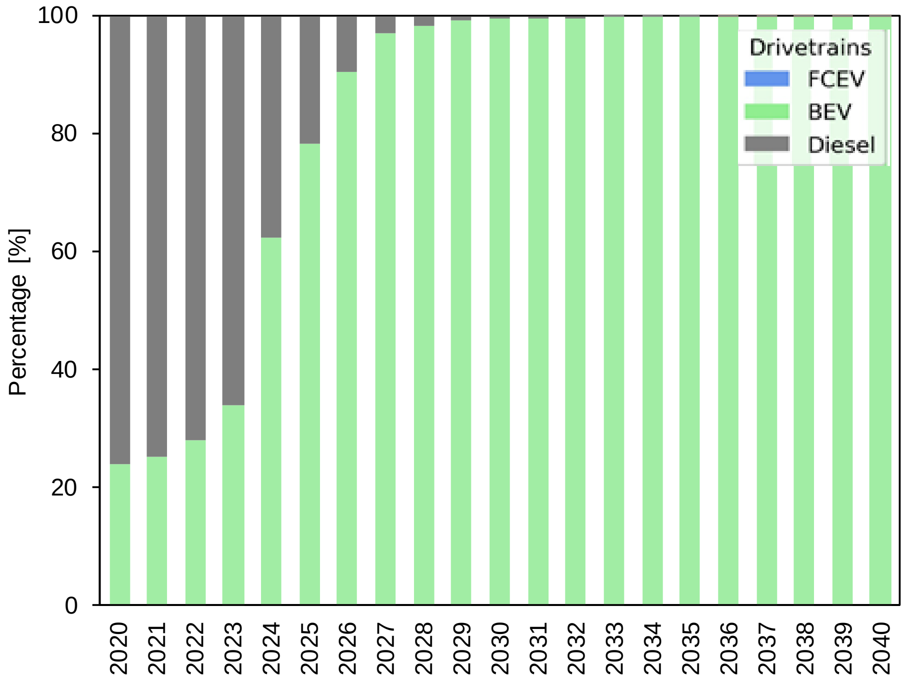

Figure 34: Aggregated techno-economic ZEV uptake potential for rigid urban, articulated regional delivery and articulated long haul trucks combined in the EU+UK.

6.3 Sensitivity analysis

A sensitivity analysis is performed to assess the sensitivity of the ZEV uptake potential to variations from the central values for most important parameters.

Additional analyses are performed based on:

- Higher battery prices
- Lower diesel prices
- Lower renewable hydrogen prices
- Higher and lower fuel cell prices
- Higher infrastructure costs
- Lower average annual / daily distance
- Higher variation in daily distance
- Higher and lower minimum share of days at which the distance is not higher than possible with BEV for a truck to be qualified for replacement by a BEV.

In this section the combined effects of these parameter variations is discussed, consisting of a best-case and a worst-case scenario. The assumptions and the detailed results of all the individual analyses are shown in Appendix I. In the results of the sensitivity analysis, the uptake potentials of BEVs and FCEVs are combined, in the form of ZEVs.

6.3.1 *Combined best-case scenario*

In this scenario the values of the parameters mentioned above are selected to be most favourable for the uptake of zero-emission trucks. This includes lower vehicle prices due to more optimistic fuel cell price developments as well as lower hydrogen and electricity prices and an optimised vehicle deployment in terms of range requirements.

Figure 35 shows the resulting uptake potential under those assumptions. For the long haul trucks, the uptake potential is almost equal compared to the central scenario. For the other vehicle types, a counter-intuitive result is observed as the uptake potential before 2030 is slightly lower than in the central scenario. This is due to the 25% reduction of annual distance. As a result of this assumption a much larger part of the fleet is indicated as a regional delivery truck instead of a long haul truck since the split point of 400 km is kept the same (see section 6.2.2). Therefore the share of vehicles with a very low mileage (which cannot cost-effectively be electrified), also increases. As a result, the total zero-emission uptake potential slightly decreases. Nevertheless, this is a modelling consequence. In reality there is not a clear split in regional delivery or long haul trucks since they are actually the same vehicle.

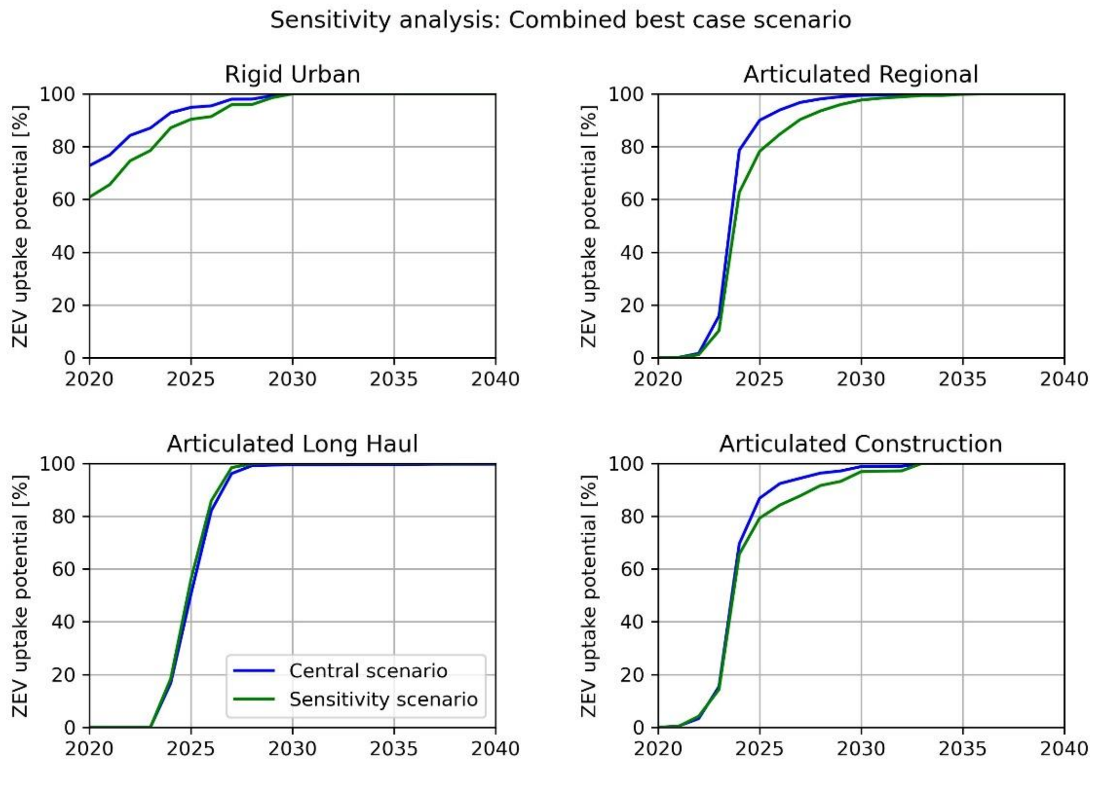

Figure 35: Aggregated results of ZE uptake in the 'combined best case scenario' compared to the 'central scenario'.

In the table below the differences in uptake potentials between the combined best case scenario and the central scenario are listed. A distinction is made between the BEVs and FCEVs such that the effect on both can be assessed separately.

Table 18: Impact on BEV and FCEV uptake potentials per vehicle type of the best case scenario compared to the central scenario.

Scenario	Vehicle type	2030		2040	
		BEV	FCEV	BEV	FCEV
Central scenario	Rigid urban	100%		100%	
	Articulated regional	99%		100%	
	Articulated long haul	99%	0%	100%	0%
	Articulated construction	99%	0%	100%	0%
Differences in combined best-case scenario	Rigid urban	0%		0%	
	Articulated regional	-2%		0%	
	Articulated long haul	+1%	0%	0%	0%
	Articulated construction	-2%	0%	0%	0%

* Consequence of modelling as explained in text above

6.3.2 *Combined worst-case scenario*

Here values for the parameters included in the sensitivity analysis are selected to not be favourable for the uptake of zero-emission trucks. Compared to the central scenario, this scenario combines non-optimised vehicle deployment, lower diesel prices, higher battery and fuel cell prices and higher electricity prices.

It can be seen in Figure 36 that the regional delivery tractor-trailer still achieves a full uptake potential, albeit that the trajectory to 100% uptake potential is three to five years slower. The other vehicle configurations see a decrease in uptake potential of 5 to 40%.

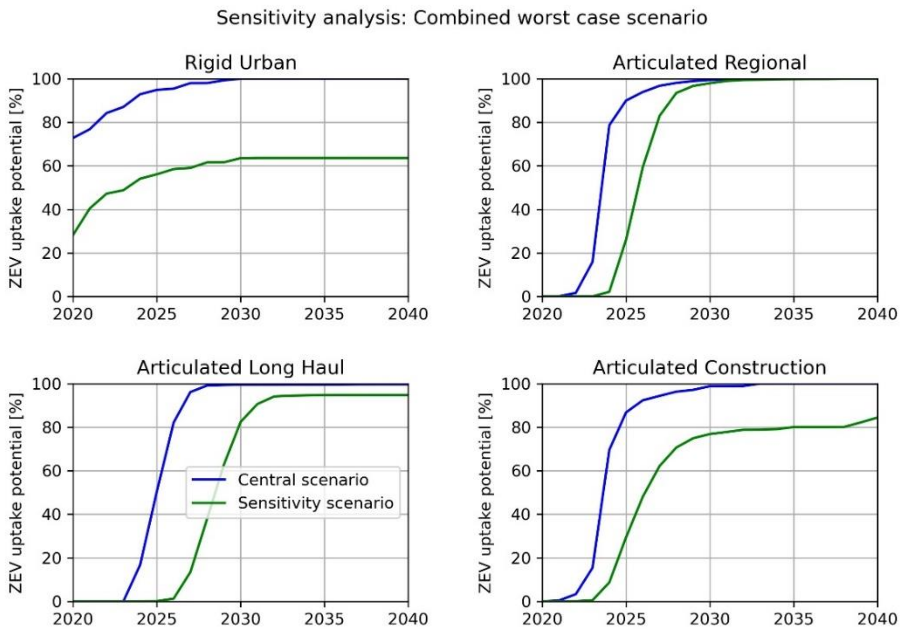

Figure 36: Aggregated results of ZE uptake for the ‘combined worst case scenario’ compared to the ‘central scenario’.

In the table below the differences in uptake potentials between the combined worst case scenario and the central scenario are listed. A distinction is made between the BEV and FCEV such that the effect on both can be assessed separately.

Table 19: Impact on BEV and FCEV uptake potentials per vehicle type of the worst case scenario compared to the central scenario.

		2030		2040	
Scenario	**Vehicle type**	**BEV**	**FCEV**	**BEV**	**FCEV**
Central scenario	Rigid urban	100%		100%	
	Articulated regional	99%		100%	
	Articulated long haul	99%	0%	100%	0%
	Articulated construction	99%	0%	100%	0%
Combined policy scenario	Rigid urban	-36%		-36%	
	Articulated regional	-1%			
	Articulated long haul	-17%	0%	-5%	0%
	Articulated construction	-22%	0%	-20%	4%

7 Policy-driven uptake scenario

Financial policy measures can affect the relative TCO differences between the diesel vehicle configurations and the ZE alternatives studied in this report, and can thereby affect outcome of techno-economic purchase decisions by fleet-owners and thus the uptake potentials for these ZE alternatives compared to the market-based scenario without policy measures described I the previous section. Three types of policy measures are selected and their effect on the uptake potential is further investigated. These are:

- Purchase subsidies: lowering the upfront vehicle cost by subsidising the purchase of ZEVs, thereby increasing their cost competitiveness (see section 7.1)
- Road tolling: differentiating country-specific road tolls with respect to CO_2 emissions, which lowers the operational costs of ZEVs and thereby affects the relative TCO differences (see section 7.2)
- CO_2 pricing: additional cost for emitting CO_2 increases the energy costs for diesel vehicles and thereby improves the relative cost competitiveness of ZEVs (see section 7.3)

The assumptions and impacts of these policies are provided in the next sections.

7.1 Impact of existing purchase subsidies

The currently existing purchase price subsidies included in the assessment for the market-based uptake potential in this report are shown in Table 20. These eight countries offer purchase grants for ZEVs for one or more of the reference vehicle configurations. There are four different ways how these are being implemented:

- A lump sum, shown under 'Funding cap' which applies to Italy and Spain where the amount is being deducted from the pre-tax vehicle purchase price;
- A share of the ZEV purchase price, with a maximum funding cap, which applies to Poland and the UK;
- A percentage share of the differential amount between the ZEV and the equivalent ICEV which applies to Austria France, Germany and The Netherlands. In France and The Netherlands there is an additional funding cap.
- Finally, France allows for an increased depreciation scheme and there is a cumulative cap on the two incentives.

These subsidies are assumed to apply up to the year 2024 when it is assumed that they would likely be phased out. Beyond this no other purchase subsidies are included.

Table 20: Purchase subsidies included in the analysis up to 2024.

	Rigid urban delivery truck			Articulated regional delivery truck / Articulated long haul truck / Articulated construction truck		
	Share of purchase price	amount in % of price difference with diesel equivalent	Funding cap	Share of purchase price	amount in % of price difference with diesel equivalent	Funding cap
Austria		80%	N/A		80%	N/A
Germany		80%	€ 350,000		80%	€ 450,000
Italy			€ 24,000			€ 24,000
Netherlands		45%	€ 84,000		45%	€ 131,900
Poland	30%		€ 43,280	30%		€ 43,280
Spain			€ 145,000			€ 160,000
United Kingdom	20%		€ 29,310	20%		€ 29,310
France*		40%	€ 50,000		40%	€ 50,000

* Additionally France has a super depreciation scheme resulting in a cost reduction of 7.5% of the purchase price, cumulatively capped at €100,000

The reduced net purchase price results in a lower TCO of the ZEVs and therefore higher uptake potential in the years up to 2024. This mechanism is especially effective in Germany and Austria due to the relatively high subsidy levels. As a result, the uptake potential for battery electric trucks in these countries is already very prominent from 2020 onwards. Due to the lack of subsidies beyond 2024, the cost competitiveness of zero emission trucks is reduced, diminishing the uptake potential temporarily in 2025. Due to cost reduction and efficiency improvements, the uptake potential in these countries with purchase subsidies picks up slowly from 2026 onwards, matching the 2024 uptake potential again in 2033.

Due to the limited number of countries in which these purchase subsidies apply, its overall effect across the EU+UK is lower than in these specific countries. As shown in Figure 37, the uptake potential increases significantly between 2020 and 2024.

From 2025 onwards after the phase-out of the subsidies the uptake potential follows that of the central scenario.

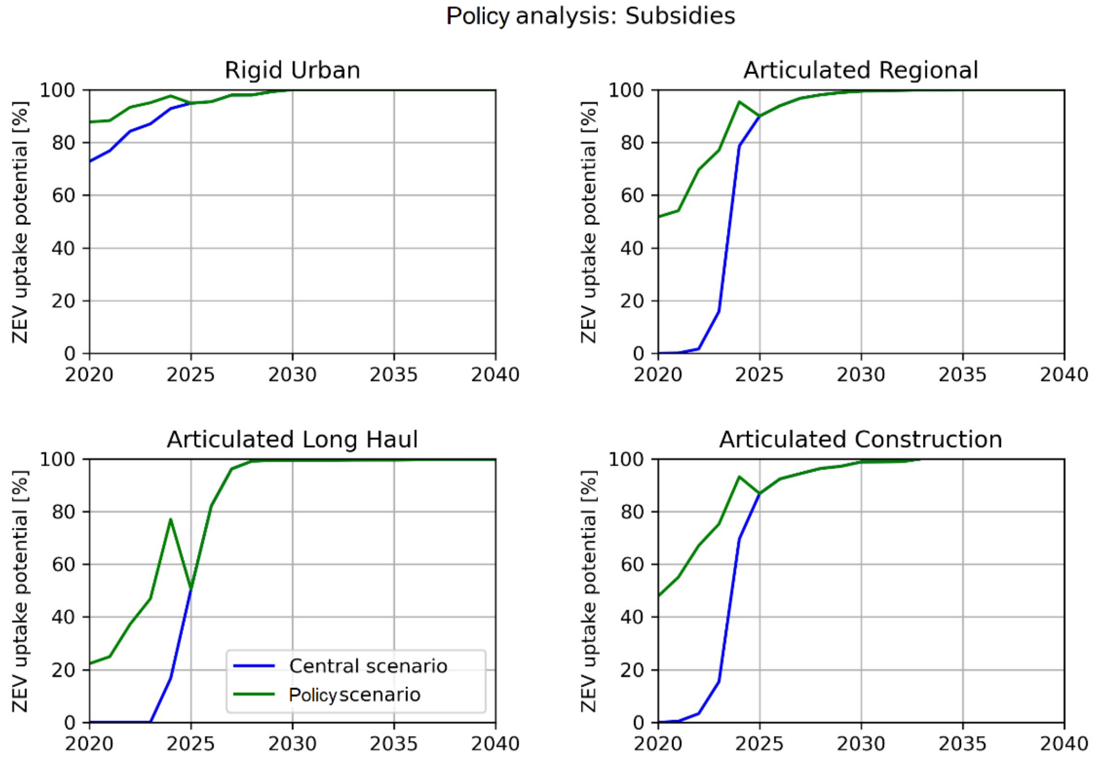

Figure 37: Effect of existing purchase subsidies on the development of uptake potential of ZEVs.

7.2 Impact of existing road tolls

The new Eurovignette Directive[15] requires EU member states that levy road tolls on trucks to differentiate them according to CO_2 emissions. In Appendix J an overview of the existing road tolling costs and future Eurovignette implementation per country can be found. Figure 38 shows the effect that these existing CO_2-based road tolls according to the Eurovignette will have on the uptake potential of zero-emission trucks in Europe, compared to the market-based scenario without policy measures. Since the road tolls are lower for zero-emission vehicles, this has a positive effect on their TCO compared to diesel trucks.

There are certain countries that currently apply a fixed toll cost per vehicle and year and others which charge a road toll per driven kilometre. Since not all the vehicle kilometres are driven on roads with tolls, the correction factors in Table 21 are applied for countries with tolls per kilometre.

It is not expected that zero-emission trucks will benefit from road toll reductions indefinitely. It is therefore assumed that the toll rates for ZEVs are increased again from 2030 until they reach the same level as diesel vehicles by 2035. As a result, the uptake potential is slightly increased for the years until 2030, in particular for the long haul trucks. In general the ZEV uptake is found to take place 1-3 years earlier.

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[15] EU Directive 1999/62/EC and amendments

Table 21: Assumed share of distances driven on roads with tolls.

Vehicle Type	Share of kilometres with road tolls
Rigid urban delivery	65%
Articulated regional delivery	85%
Articulated long haul	95%
Articulated construction	65%

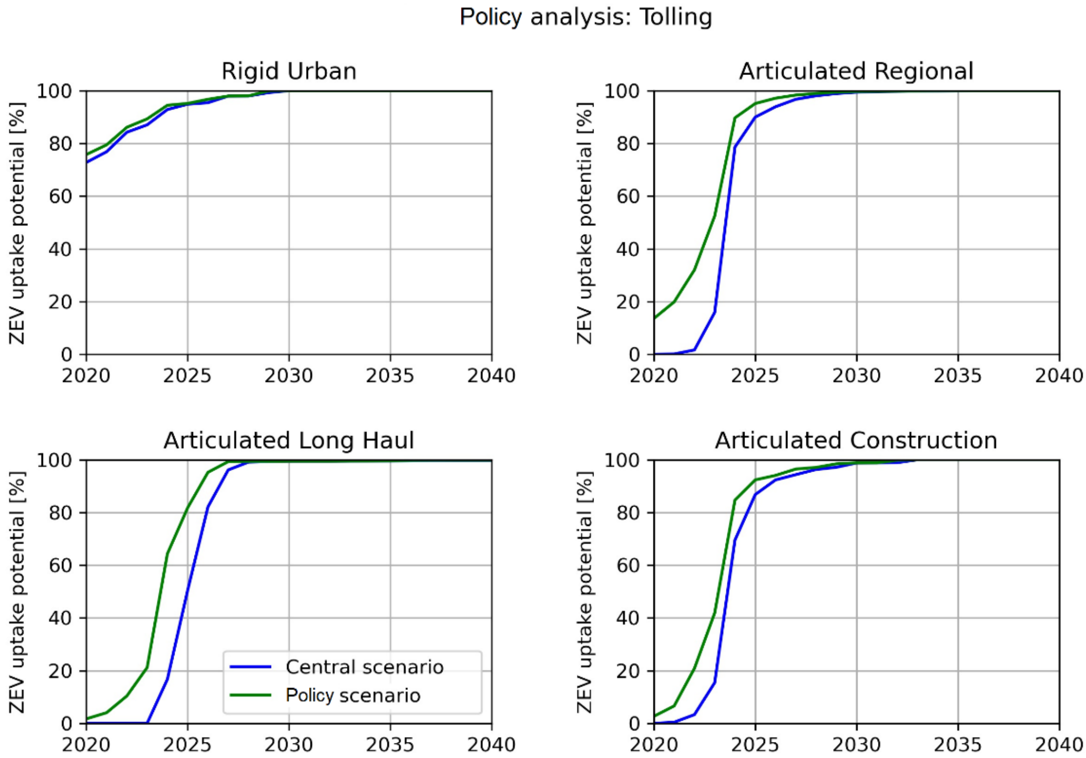

Figure 38: Effect of existing road tolling on the development of uptake potential of ZEVs.

7.3 Impact of CO_2 pricing of transport fuels

The upcoming emissions trading system for road transport and buildings will introduce a CO_2 price for fossil fuels in the road transport sector. The detailed regulation is currently being negotiated by the European institutions, but all institutions have agreed to a carbon market for transport fuels, at the very least for commercial vehicles. An introduction of the system by the end of the 2020s is therefore foreseeable.

In this report, a CO_2 price is assumed to be applied from 2026 onwards for all EU member states as this is the mid-point between the position of the European Parliament and the Council. The assumed CO_2 price is shown in Figure 39. It is based on a model developed by Vivid Economics (unpublished). The chosen scenario includes an initial price cap of 50 EUR/tCO_2 in the year 2026 as this comes closest to the adopted position by the European Parliament. Following the position of the Council, it is then assumed that the cap will increase by 10 EUR/tCO_2 annually.

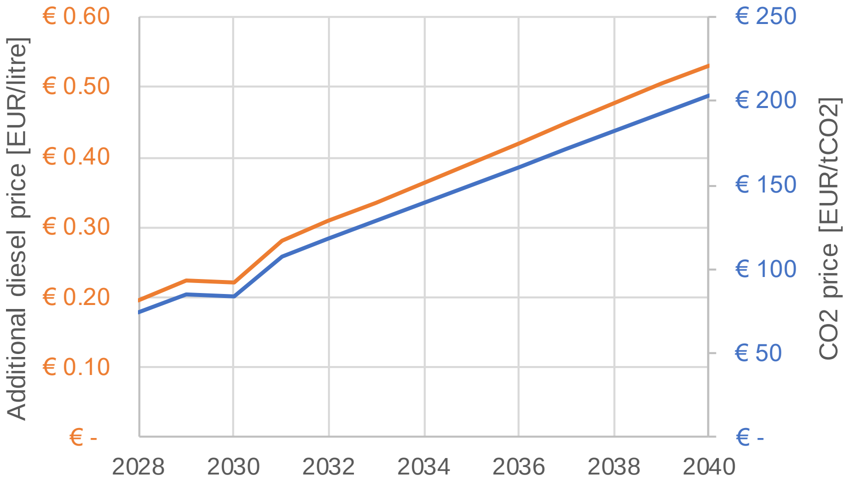

Figure 39: Assumed development of the CO2 price under the ETS for road transport and buildings and the resulting penalty for diesel

As a result of the increased diesel price, the relative cost competitiveness for zero-emission alternatives improves. Nevertheless the impact on the uptake potential pace is negligible. This is because the most prevalent impact on the uptake potential of ZEVs is the cost reduction of batteries, which already yields a very high techno-economic uptake potential by the time the CO_2 price is implemented.

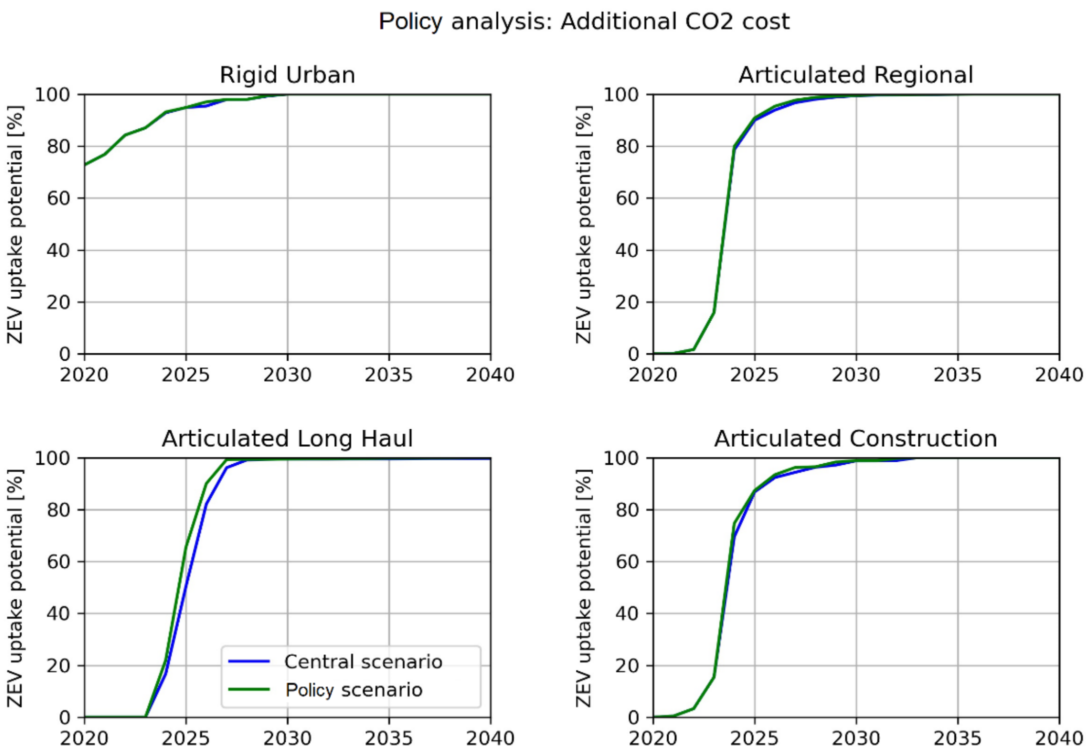

Figure 40: Impact on the annual ZEV uptake potential of a 'CO_2 pricing' scenario, effective as of 2028.

7.4 Combined policy scenario

In case all three policies discussed above are taken into account, the policy-driven uptake potential pace is increased on the short to mid-term (see Figure 41). This combined impact is mainly driven by the subsidies.

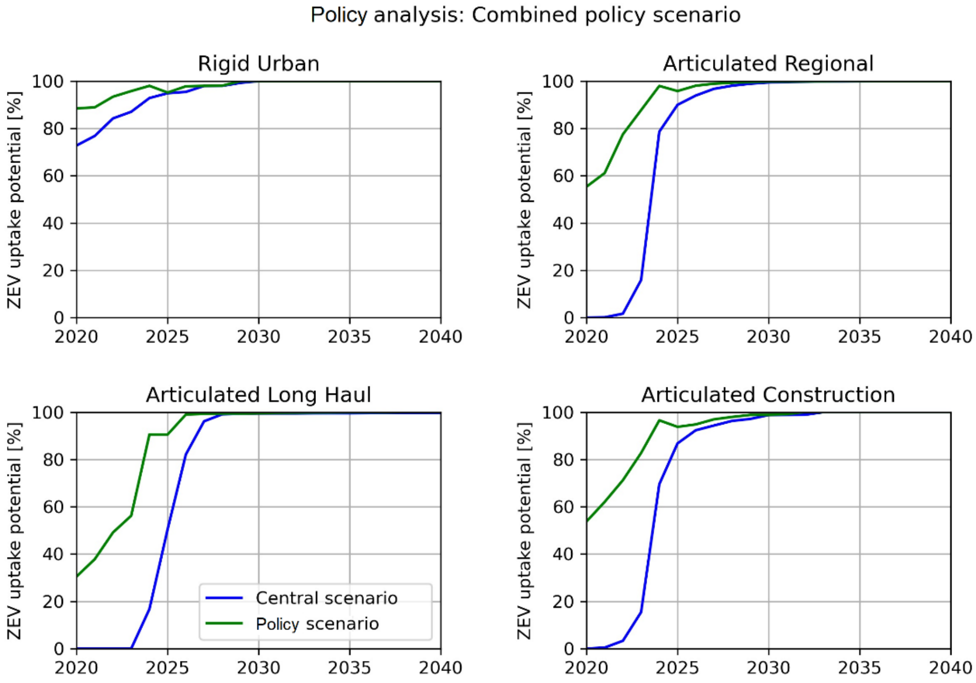

Figure 41: Impact of the combination of existing subsidies and CO_2-based road tolls and a future CO_2 price for road fuels on the ZEV uptake potential per vehicle type.

In the table below the differences in uptake potential in for various scenarios are listed relative to the central scenario. A distinction is made between the BEVs and FCEVs such that the effect on both can be assessed separately. However, since the policies only affect the uptake potential before 2030, the effects of the combined policy scenarios are included in this table are zero.

Table 22: Impact on BEV and FCEV uptake potentials per vehicle type of the combined policy scenario compared to the central scenario.

Scenario	Vehicle type	2030 BEV	2030 FCEV	2040 BEV	2040 FCEV
Central scenario	Rigid urban	100%		100%	
	Articulated regional	99%		100%	
	Articulated long haul	99%	0%	100%	0%
	Articulated construction	99%	0%	100%	0%
Combined policy scenario	Rigid urban	0%		0%	
	Articulated regional	0%		0%	
	Articulated long haul	0%	0%	0%	0%
	Articulated construction	0%	0%	0%	0%

With these three policies in place, the overall uptake potential of rigid urban delivery trucks, articulated regional delivery trucks and articulated long haul trucks together would reach close to 100% at a similar time as without policies (see Figure 42). However, in the 2020s, the techno-economic uptake potential is significantly higher than in the central scenario. In 2020 the uptake potential in the central scenario is 24% compared to 66% in this situation with the three additional policies.

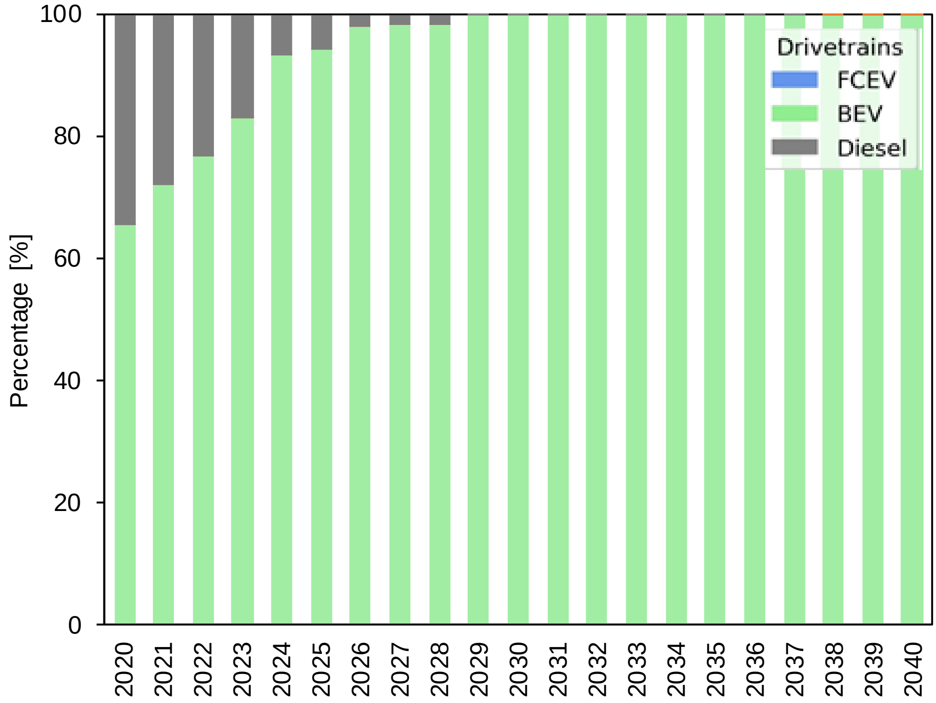

Figure 42: Aggregated techno-economic ZEV uptake potential for rigid urban, articulated regional delivery and articulated long haul trucks combined in the EU+UK in a situation with three additional active policies.

8 Other uptake drivers and barriers

In this report, the techno-economic market uptake potential for zero-emission trucks has been analysed. As explained in section 1.5, this is determined by the affordability and applicability of vehicles with different drivetrain types. This potential uptake could be different from the future uptake of the various drivetrain types into the fleet, as this depends on many factors that are not accounted for in this analysis, such as the availability of vehicles, the roll-out of charging and refuelling infrastructure, and the acceptance by transport operators. These conditions also need to be met in order for the future uptake to reach the uptake potential. In this section these factors are addressed qualitatively.

8.1 Availability of vehicles

8.1.1 Production scale

To realise a large upscale of ZEVs into the HDV fleet, manufactures will have to produce sufficient numbers of ZE vehicles to meet that demand. This requires changes in the total vehicle production chain from component manufacturers to final assembly. Currently, production volumes of zero-emission trucks are so limited that certain components are produced in small batches and assembly is done partly outside of the standard automated production lines. This results in higher costs and lower volumes. Before ZEVs can be produced in high volumes at acceptable costs, production processes and manufacturing equipment have to be adapted to facilitate the production of such vehicles.

8.1.2 Materials and supply chain

As explained in sections 4.2.1 and 4.2.3, the production of batteries and fuel cells requires critical materials that are extracted and processed in a limited number of countries worldwide (IEA, 2021). The current inability for raw material supply to keep up with the demand, partly due to the present situation in Ukraine, has led to a vast increase of prices for essential battery materials such as nickel, cobalt, and lithium.

This price increase is expected to incentivise new production of materials as this is becoming more profitable. This additional supply is expected to have a dampening effect on the material prices later on. The magnitude of this effect and time by which it can be expected remains uncertain.

The (temporary) shortage of critical materials would not only lead to an increase in production costs. This is already accounted for in the sensitivity analysis for which higher battery prices are assumed than in the main scenario. It could also potentially limit the amount of vehicles which can be produced and therefore the availability of zero emission trucks. This may limit their actual uptake, even if there is a clear benefit in terms of TCO.

8.2 Availability of infrastructure

Transport operators of ZEVs require adequate infrastructure to charge or refuel their vehicles. Technological developments to increase charging power capabilities of rechargers and flow of hydrogen filling stations are ongoing and look promising.

Charging power levels of up to 1 MW and higher are currently already being commercialised. This would enable trucks to recharge sufficiently during the mandatory 45 minutes breaks to drive for an additional 4.5 hours until the next mandatory break.

However, to apply the power levels that can be delivered by the rechargers, the electricity grid needs to have sufficient capacity at the required time and location. Such capacity may not always be available on locations where rechargers will be required, such as service areas, overnight truck parkings, business parks and private depots. Upgrading the electricity grid will require significant investments of time and budgets. When this is not realised in time (i.e. when the uptake starts to rise), it may delay the uptake of battery electric trucks. On the upside, other sectors such as the industry and the buildings sector are also likely in need of electricity grid upgrades to enable the energy transition, so that the uptake of ZEVs may benefit from investments made for a broader purpose. On the downside, however, limited resources may result in competition with these other sectors for grid reinforcements.

As for renewable hydrogen, transport and distribution may be a challenging factor. Hydrogen can be transported by road in tube trailers, through pipelines or produced locally from electricity. All these options come with their own challenges. Tube trailers can only move relatively small amounts of hydrogen, requiring many round trips from the hydrogen source to the refuelling station. Due to costs constraints, distribution through pipelines is only possible at locations where the station is sufficiently close to a hydrogen pipeline that is used for other means, such as industry. Even then, the hydrogen will likely need purification for it to be used in fuel cells. Local production requires sufficient electric power, which again is currently not available at locations where refuelling stations are needed. Besides electricity, such a site would also require hydrogen storage capacity.

8.3 Acceptance by transport operators

8.3.1 Physical space for charging

For battery electric trucks, part of the fleet will be recharged overnight at or close to private depots. This means that sufficient physical space is required to park all vehicles near a charger, and for a long period of charging time (approximately eight hours). Not in all locations this space will be available.

8.3.2 Skilled personnel for maintenance

Some transport companies maintain their own vehicle fleet. Once zero emission trucks are entering into their fleet, maintenance personnel will have to be skilled to maintain two or potentially even three different types of drivetrains. At the same time, maintenance equipment has to be available for all these drivetrains.

8.3.3 Brand / dealer loyalty

Especially during the early stages of the transition to zero emission trucks, not all brands may have vehicles available that meet the requirements of certain transport operators. Due to brand loyalty, operators may be reluctant to acquire ZEVs until these are available from that specific brand.

8.3.4 *Flexibility of vehicles*

The technical uptake potential of zero emission trucks determined in section 6 is based on the average way in which these trucks are currently being deployed, taking into account a spread in average daily distances as well as day-to-day variations. However, this is still a simplification of reality. For instance, in reality a certain trip may be changed or extended at the last moment. If such a change was not accounted for, the truck may not have been charged sufficiently to cover that extra trip without additional time needed for charging. There may be also trucks that are operated around the clock by different drivers. Compared to diesel vehicles and to a lesser extent FCEVs, BEVs require more elaborate planning due to their range limitations.

Acquiring a truck with more battery capacity will provide more flexibility, but this flexibility comes at a cost. Due to the larger battery these vehicles will be more expensive, and the higher weight reduces the energy efficiency. Therefore, transport operators may wait for battery costs and weight to come down and purchase trucks with a larger battery for the same price. Effectively this would slow down the transition.

8.3.5 *Uncertainty over new technology*

Diesel trucks have been the standard in Europe for many decades. It is a mature and reliable technology. Shifting to new technologies with (perceived) start up issues, may hold some transport operators back even if this new technology is well applicable and cheaper than conventional diesel drivetrains.

8.3.6 *Uncertainty about energy cost development*

The TCO model which is used in this report calculates the energy cost over the first use period of the truck. As is explained in section 4.3 the energy prices vary over time. Therefore, any price changes in the future influence the TCO of a truck bought in the present. For example, in the year of purchase a diesel truck might have a lower TCO than an FCEV using the price levels in that year. But if the price development assumptions over a 5 year period are considered, the FCEV might actually have a more favourable TCO as compared to the diesel truck.

This effect is captured in the TCO model since the techno-economic potential is evaluated over the first use period of the truck. Although the results are fairly robust, meaning that their sensitivity to deviations from the central scenario are limited, a potential investor may be held back to invest in new technology.

8.4 Other drivers

The previous sections addressed the main barriers that may prevent the uptake of ZEVs into the HDV fleet. There are also potential enabling factors that positively influence the uptake, aside from the policy measures discussed in section 7 . For example, city centres that suffer from air pollution may introduce zero-emission areas for HDVs which supply stores. Public awareness and social responsibility can also be drivers for the ZEV uptake. In a climate where the environmental impact of transport is increasingly recognised, logistics companies might consider to use ZEVs even if the TCO of these exceeds that of diesel trucks.

9 Conclusions and key findings

Based on the assessments made in this report with respect to the techno-economic uptake potential for ZE trucks, the following conclusions and recommendations can be made:

9.1 Overall findings

- Determining the uptake of zero-emission trucks requires a large number of assumptions, which can have a wider range of effects on the results.
- By the year 2040, BEVs are expected to be 5% to 15% more expensive than equivalent diesel trucks in terms of upfront vehicle prices. Purchase prices of FCEVs are estimated to be 15% more expensive by that time.
- In the central scenario, EU+UK average electricity costs (including infrastructure costs) per unit of energy are expected to be 1.4 to 1.9 times higher than diesel costs by 2030 (depending on the ratio between depot charging and fast charging) and a factor 1.4 to 1.5 by 2040 (respectively 0.17-0.23 €/kWh and 0.17-0.18 €/kWh). End-user hydrogen prices per unit of energy at the refuelling station are assumed to be a factor 1.8 and 1.4 times higher than diesel in 2030 and 2040 respectively (7.1 €/kg in 2030 and 5.6 €/kg in 2040). However, BEVs and FCEVs have a lower energy consumption than internal combustion engine vehicles (here diesel) trucks, which more than offsets the slightly higher cost per unit of energy. As a result the energy costs per kilometre of BEVs are 1.1 to 3.3 times lower than those of diesel vehicles by 2030 depending on the vehicle segment. In 2040 electricity cost per kilometre are a factor 1.4 to 3.5 lower than those of diesel. As a result of the higher energy efficiency of the vehicle, the energy costs per kilometre of FCEVs are about equal to that of the equivalent diesel vehicle in 2030 (factor 0.9 to 1.1) and slightly lower than those of the diesel vehicle by 2040 (factor 1.2 to 1.4). As energy prices vary between countries, these factors are also different in individual countries.
- Looking at the total cost of ownership, from about 2030 onwards, BEVs are expected to be the most cost-effective option for all of the vehicle types assessed in this report. This would even be the case if battery prices do not come down as fast as expected, diesel prices would be relatively low or electricity prices relatively high. However, due to range limitations, battery electric vehicles can potentially not be used for longer trips which make them unsuitable for replacing trucks with high average daily mileages or large distances on certain days. This however concerns an extremely low number of trucks.
- FCEVs can be a zero-emission alternative for diesel trucks that drive very large distances at least part of the time. However, it is expected that these will not be cost-competitive with diesel. Based on the assumptions made in this report, FCEVs will remain more expensive than diesel trucks and renewable hydrogen will continue to be more expensive than diesel. The lower energy consumption of FCEVs compared to diesel trucks is not sufficient to compensate for these higher costs. Even at lower hydrogen prices or lower fuel cell costs, FCEVs only become the most cost-effective technology from 2030 onwards for a very limited share of the long haul truck fleet. In three countries the uptake potential of FCEVs is determined to be more than 1% with a maximum of 3%.

9.2 Market-driven uptake scenario

- The aggregated uptake potential of ZEVs for the rigid urban truck and the articulated regional and long haul truck categories reaches 99.8% by 2035. For the articulated construction trucks, a 100% ZEV uptake potential is reached in 2033. Nearly the complete uptake potential consists of BEVs, as FCEVs are found not to be the most cost-competitive technology for any form of deployment where BEVs have no range limitations.
- Despite the differences in vehicle deployment and energy prices, the differences in uptake potential between the regions in Europe are found to be limited. The maximum difference between regions is approximately a three-year delay and the final uptake potential is equal in all regions.
- It is found that the TCO of battery electric trucks will be so much lower than that of diesel trucks that the uptake potential is hardly sensitive to higher battery prices and fuel cell prices, higher electricity prices or lower diesel prices.
- For the uptake potential of BEVs, it is very important that the battery dimensioning matches the vehicle range requirements. The overall TCO of battery electric trucks is the lowest when the maximum range allowed by the battery is used on the majority of the driving days. This means that the uptake potential of BEVs benefits from as little variation in daily distance as possible and a battery capacity that is sufficient for these distances. In other words, a transport company with a fleet may optimize the trips for the BEVs in the fleet, which would increase not only the applicability but also the cost-competitiveness for these vehicles and would lead to an earlier ZEV uptake.
  - In the central scenario it is assumed that the variation in daily distance can be reduced by 30% compared to the way that trucks are currently being used. If such an improvement would not be possible, the uptake potential could drop by 20% for urban rigid trucks. However, if the vehicles dimensioned for this study would have been fitted with larger batteries, the sensitivity to changes in the daily distance variation would have been lower.
  - A similar conclusion can be drawn for the sensitivity of the uptake potential to the share of trips that a ZEV would have to be able to replace. The central scenario is based on the assumption that ZEVs should be able to replace at least 90% of the daily distances that a diesel truck currently makes. This means that up to 10% of daily distances cannot be replaced by the ZEV. In case the condition is that a ZEV should be able to cover 95% of trips of its diesel equivalent, the uptake potential also drops by 20% for the urban rigid trucks. Fitting these trucks with larger batteries would increase the TCO of these BEVs, but given their significant TCO advantage over diesel trucks after some years, this would lead to a lower drop in uptake potential than 20%.

9.3 Policy-driven uptake scenario

- An assessment of the impact of existing purchase subsidy schemes in seven different European countries shows that these increase the uptake potential significantly during the early years. Since these subsidies are only assumed to apply until 2024, the uptake potential beyond 2024 is not affected.
- The effect of existing CO_2-based tolling schemes in European countries is also found to be significant up to 2030, as the uptake potential is brought forward by one to three years.

- A possible future CO_2 pricing scheme for buildings and road transport sectors (ETS2) leads to higher fuel costs for diesel trucks. As a result of the increased diesel price, the relative cost-competitiveness for zero-emission alternatives improves. Nevertheless the impact on the assessed uptake potential pace is negligible, as this measure is expected to implemented by 2028. By that time the cost reduction of batteries, which is the most prevalent factor impacting the uptake potential of ZEVs, will already have led to very high uptake potentials close to 100%.

9.4 Other uptake drivers and barriers

- Although it is concluded that FCEVs are not the most cost effective drivetrain for any of the types of deployment assessed, it does not mean that FCEVs will not play a role in the decarbonisation of the road freight sector. There are other types of vehicles, such as vocational and special purpose vehicles that are out of scope of this study for which hydrogen or other drivetrain technologies may be the most cost-effective option. Moreover, in certain situations, the most cost effective option may not be possible to implement. For example in locations where charging infrastructure for BEVs cannot not be realised in a cost effective manner, other technologies such as FCEVs may be the best option for decarbonisation.
- The true uptake of zero-emission trucks will likely differ from the techno-economic uptake potential estimated in this study. Besides the factors on which the uptake potential is based in this study i.e. the cost-effectiveness and applicability, there are more factors that will determine the actual uptake of zero-emission trucks, such as the availability of vehicles, sufficient raw materials, well working supply chains and production facilities, sufficient infrastructure, acceptance by transport operators, other policies that assessed not in this study (e.g. zero-emission zones) and public awareness and social responsibility.

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11 Signature

The Hague, 3 October 2022

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A Vehicle sizing and power train dimensioning

The tables in this appendix provide the detailed input data for the determination of the vehicle size and dimensioning of the power train. For further information refer to section 2.

Table 23 Empty mass in kg for the reference vehicles in 2020, 2030 and 2040

Parameter [kg]	Drivetrain	2020	2030	2040
Rigid Urban Truck	Diesel	4,669	4,436	4,436
	BEV medium	4,474	3,992	3,700
	BEV large	4,631	4,096	3,780
Articulated Truck Regional Delivery	Diesel	15,729	15,318	15,318
	BEV medium	16,511	15,095	14,439
	BEV large	17,271	15,506	14,732
Articulated Truck Long Haul	Diesel	15,729	15,318	15,318
	BEV medium	18,402	16,084	15,149
	BEV large	20,934	17,295	16,027
	FCEV	16,884	16,083	15,609
Construction Truck	Diesel	14,329	13,918	13,918
	BEV medium	14,306	13,349	12,781
	BEV large	15,605	14,077	13,284
	FCEV	14,722	14,075	13,606

Table 24: Vehicle sizing and dimensioning of the powertrain for the rigid urban delivery truck.

Parameter	Unit	Drivetrain	2020	2030	2040
Truck (+trailer) empty mass	kg	Diesel	4,669	4,436	4,436
		BEV medium	4,474	3,992	3,700
		BEV large	4,631	4,096	3,780
Engine/motor rated power	kW	Diesel	180	180	180
		BEV medium	190	190	190
		BEV large	190	190	190
Nominal battery capacity	kWh	BEV medium	126	110	109
		BEV large	155	139	139

Table 25: Vehicle sizing and dimensioning of the powertrain for the articulated regional delivery truck.

Parameter	Unit	Drivetrain	2020	2030	2040
Truck (+trailer) empty mass	kg	Diesel	15,729	15,318	15,318
		BEV medium	16,511	15,095	14,439
		BEV large	17,271	15,506	14,732
Engine/motor rated power	kW	Diesel	350	350	350
		BEV medium	370	370	370
		BEV large	370	370	370
Nominal battery capacity	kWh	BEV medium	429	350	349
		BEV large	569	465	459

Table 26: Vehicle sizing and dimensioning of the powertrain for the articulated long haul truck.

Parameter	Unit	Drivetrain	2020	2030	2040
Truck (+trailer) empty mass	kg	Diesel	15,729	15,318	15,318
		BEV medium	18,402	16,084	15,149
		BEV large	20,934	17,295	16,027
		FCEV	16,884	16,083	15,609
Engine/motor rated power	kW	Diesel	350	350	350
		BEV medium	370	370	370
		BEV large	370	370	370
		FCEV	370	370	370
Nominal battery capacity	kWh	BEV medium	777	627	616
		BEV large	1,243	966	946
		FCEV	140	140	140
Fuel-cell rated power	kW	FCEV	240	240	240
Hydrogen storage	kg	FCEV	60	60	60

Table 27: Vehicle sizing and dimensioning of the powertrain for the articulated construction truck.

Parameter	Unit	Drivetrain	2020	2030	2040
Truck (+trailer) empty mass	kg	Diesel	14,329	13,918	13,918
		BEV medium	14,306	13,349	12,781
		BEV large	15,605	14,077	13,284
		FCEV	14,722	14,075	13,606
Engine/motor rated power	kW	Diesel	350	350	350
		BEV medium	370	370	370
		BEV large	370	370	370
		FCEV	370	370	370
Nominal battery capacity	kWh	BEV medium	281	253	252
		BEV large	520	457	441
		FCEV	140	140	140
Fuel-cell rated power	kW	FCEV	240	240	240
Hydrogen storage	kg	FCEV	60	60	60

B Energy efficiency improving technologies

Future trucks will be equipped with energy efficiency improvement technologies. The tables in this appendix show which of the available technologies are assumed to be applied on trucks in 2030 and 2040. The abbreviations for the technologies in Table 28 and Table 30 are explained in Table 29. The data is based on an earlier study performed by TNO (TNO, 2018).

Table 28: Energy efficiency technologies accounted for in this study.

	2030			**2040**		
	Diesel	BEV	FCEV	Diesel	BEV	FCEV
AERO1	Yes	Yes	Yes	Yes	Yes	Yes
AERO2	Yes	Yes	Yes	Yes	Yes	Yes
AERO3	Yes	Yes	Yes	Yes	Yes	Yes
AERO5	No	Yes	Yes	No	Yes	Yes
AERO6	Yes	Yes	Yes	Yes	Yes	Yes
AERO7	Yes	Yes	Yes	Yes	Yes	Yes
MASS1	Yes	Yes	Yes	Yes	No	No
MASS2	No	No	No	No	Yes	Yes
AUX1	Yes	Yes	Yes	Yes	Yes	Yes
AUX2	Yes	Yes	Yes	Yes	Yes	Yes
AUX3	Yes	Yes	Yes	Yes	Yes	Yes
AUX4	Yes	Yes	Yes	Yes	Yes	Yes
TYRES1	Yes	Yes	Yes	Yes	Yes	Yes
TYRES2	Yes	Yes	Yes	Yes	Yes	Yes
TYRES3	Yes	Yes	Yes	Yes	Yes	Yes
TYRES4	Yes	Yes	Yes	Yes	Yes	Yes
TYRES7	Yes	Yes	Yes	Yes	Yes	Yes
TRANS1	Yes	No	No	Yes	No	No
ENG2	Yes	No	No	Yes	No	No
ENG3	Yes	No	No	Yes	No	No

Table 29: Impact of energy efficiency technologies.

			Reference unit	Rigid 16t truck	Articulated 40/44t truck
	AERO1	Roof spoiler plus side flaps	$C_d \cdot A$ [m^2]	-15%	-15%
	AERO2	Side and underbody panel at truck chassis		-4%	-4%
	AERO3	Aerodynamic mud flaps		-4%	-4%
	AERO5	Redesign, longer and rounded vehicle front		-6%	-6%
	AERO6	Side and underbody panels at trailer chassis		-10%	-10%
	AERO7	Boat tail short, additional		-7%	-7%
	MASS1	5% Mass reduction (truck/tractor)	M_{empty} [kg]	-5%	-5%
	MASS2	10% Mass reduction (truck/tractor)		-10%	-10%
	AUX1	Electric hydraulic power steering	P_{aux} [kW]	-4%	-4%
	AUX2	LED lighting		-1%	-1%
	AUX3	Air compressor		-14%	-14%
	AUX4	Cooling fan		-3%	-3%
	TYRES1	Low rolling resistance tyres on truck/tractor	C_{rr} [kg/ton]	-15%	-13%
	TYRES2	Low rolling resistance tyres on truck/tractor + trailer		-15%	-26%
	TYRES3	Tyre pressure monitoring system (TPMS) on truck		-2%	-1.6%
	TYRES4	Tyre pressure monitoring system (TPMS) on truck and trailer		-4%	-3.2%
	TYRES7	Wide base single tyres		-2%	-2%
	TRANS1	Reduced losses (lubricants, design)	$\eta_{transmission}$	1%.	1%.
	ENG2	Friction reduction + improved water and oil pumps	η_{motor}	1%.	1.1%.
	ENG3	Improved lubricants		5%.	5%.

Table 30: Costs of energy efficiency technologies in $€_{2020}$ based on (TNO, 2018).

	VECTO vehicle group			
	4	5	9	10
AERO1	1,959	1,959	1,959	1,959
AERO2	734	734	734	734
AERO3	979	979	979	979
AERO5	39	98	59	118
AERO6		196		196
AERO7		2,938		2,938
MASS1	778	1,387	1,373	1,387
MASS2	1,555	2,772	2,747	2,772
AUX1	224	224	224	224
AUX2	224	224	224	224
AUX3	224	224	224	224
AUX4	224	224	224	224
TYRES1	137	343	206	411
TYRES2		343		411
TYRES3	137	343	206	411
TYRES4		343		411
TYRES7	-34	-69	-34	-69
TRANS1	245			
ENG2	1,028	1,028	1,028	1,028
ENG3	23	23	23	23

C Energy consumption based on ADVANCE model

The energy consumption in this report is modelled using ADVANCE (TNO, 2002), a simulation model which was developed by TNO. This is a forward calculating simulation tool with a modular structure. It has the capability to model the load dependant efficiency of a vehicle for a specified trip profile in terms of vehicle speed and road slope while the effects of environmental conditions are taken into account. Where simple energy consumption tools determine their results through backward calculation towards the required power from the engine, ADVANCE is capable to determine the throttle position necessary to follow the required vehicle speed (forward calculation). This means that if the vehicle has insufficient power available to meet the desired speed, the vehicle will accelerate at full throttle until the required speed trace is met. All efficiencies that play a role in the determination of the energy consumption are modelled, including the dependencies of these efficiencies for other vehicle parameters or ambient conditions.
For more detailed information on ADVANCE, refer to (TNO, 2002).

C.1 Assumptions

C.1.1 Aerodynamic and road loss properties

The aerodynamic and road loss properties of the reference trucks are presented in Table 31. Note the difference between the driven and non-driven tyre resistance. Driven tyres have higher rolling resistance to ensure power of the engine can be transferred with minimal slip to the road surface. Trailer tyres are chosen to be equal to the non-driven tyres. Additional tyre friction from cornering is not taken into account.

Table 31: Aerodynamic and road loss properties in the reference year.

Vehicle type	Aerodynamic shape Cd·A [m²]	Tire resistance – driven wheels [kg/t]	Tire resistance – non-driven wheels [kg/t]	Tire resistance trailer [kg/t]
Rigid urban	3.45	0.0056	0.0048	0.0052
Articulated regional	4.73	0.0057	0.0049	0.0052
Articulated long haul	4.73	0.0057	0.0049	0.0052
Articulated construction	4.08	0.0057	0.0049	0.0052

Aerodynamic properties are given by the product of the frontal area A and the drag coefficient Cd. For the articulated trucks, the Cd·A value takes in account the effect of the trailer shape. Average cross-wind effects are not included in the simulation runs.

C.1.2 Auxiliary power consumption

To capture the energy consumption of non-modelled truck components, an auxiliary power consumption is defined for each truck. Auxiliary power consumption captures the effect of:

- Motor cooling fan
- Motor/battery cooling pump
- Air compressor
- Steering pump
- Lights
- Airconditioning
- Cabin heating

The auxiliary energy consumption for the different trucks in the reference year is defined in Table 32.

Table 32: Auxiliary power consumption values.

Vehicle type	Diesel driveline [W]	Electric driveline [W]
Rigid urban	3,557	2,938
Articulated regional	4,649	4,183
Articulated long haul	5,029	4,626
Articulated construction	5,203	4,833

C.1.3 Efficiency of components

Driveline components in the trucks have associated energy losses dependant on the operating point. These working point dependant losses are modelled in various ways. Gearbox efficiencies are generally modelled using a fixed efficiency across the entire operational range.

For the purpose of this study, diesel and electric motors are modelled using the Willans line approach (TNO, 2002). The Willans line defines a fixed offset corresponding to the friction losses and a slope corresponding to the load dependant losses. The calculated energy consumption of the different trucks over the years is shown in Figure 7 of section 3.2.

D Country-specific vehicle deployment

This appendix describes the country-specific data on the average new registrations of vehicles, based on the TRACCS database (Emisia, 2013). These data are used to determine the range requirements (see section 5.1) and to apply a country- respectively regional weighting in the end results (see section 6.1.2). In TRACCS, a distinction is made between rigid trucks and truck semi-trailers (TST).

Table 33: Country-specific TRACCS data on average new vehicle registrations, used for aggregating countries and regions

Region	Country	Average new registrations Rigid 14-20 tonnes	Average new registrations TST 30-50 tonnes
Germany	Germany	9,273 *(20%)*	17,729 *(19%)*
France	France	11,490 *(25%)*	18,240 *(19%)*
Western Europe	Austria	501	3,667
	Belgium	1,658	2,812
	Ireland	154	-
	Luxembourg	182	3
	Netherlands	1,813	311
	United Kingdom	3,163	18,536
	Total	7,471 *(16%)*	25,330 *(27%)*
Northern Europe	Denmark	328	2,847
	Finland	723	372
	Sweden	1,062	480
	Total	*2,112 (5%)*	*3,699 (4%)*
Southern Europe	Cyprus	72	8
	Greece	494	394
	Italy	3,328	5,235
	Malta	10	10
	Portugal	1,109	-
	Spain	2,097	16,198
	Total	*7,111 (15%)*	*21,845 (23%)*
Central Europe	Czech Republic	1,340	3,080
	Poland	1,918	1,995
	Slovakia	484	100
	Slovenia	249	31
	Total	*3,990 (9%)*	*5,206 (5%)*
Eastern Europe	Bulgaria	1,414	196
	Croatia	285	19
	Estonia	-	-
	Hungary	618	2,876
	Latvia	837	-
	Lithuania	433	105
	Romania	1,267	8
	Total	*4,854 (10%)*	*3,203 (3%)*

As the same truck can be categorised differently between countries, the articulated truck numbers are obtained by combining the numbers for the 34-40 ton and 40-50 ton truck categories in TRACCS. New registrations are determined by summing values for these variants. For the average annual mileage, the weighted mean is used between the two truck variants based on the population of the respective age bin.

Table 34: Country-specific data on average annual mileage in km (ICCT).

Country	Average annual mileage Rigid 14-20 tonnes	Average annual mileage Articulated 30-50 tonnes
Belgium	70,779	133,027
Bulgaria	71,066	125,900
Czech Republic	83,909	140,016
Denmark	70,269	129,974
Germany	66,277	126,608
Estonia	78,634	145,913
Ireland	76,996	142,865
Greece	79,218	165,689
Spain	78,634	145,913
France	70,077	130,818
Croatia	81,252	161,525
Italy	85,133	171,282
Cyprus	66,805	127,322
Latvia	80,074	136,083
Lithuania	79,561	127,938
Luxembourg	69,282	129,364
Hungary	83,413	145,836
Malta	66,271	126,011
Netherlands	69,717	128,961
Austria	65,903	122,775
Poland	76,730	148,839
Portugal	86,790	156,609
Romania	85,245	170,557
Slovenia	75,715	128,520
Slovakia	81,356	147,090
Finland	74,156	145,201
Sweden	70,828	132,594
United Kingdom	76,996	142,865
EU+UK average	**75,753**	**140,575**

Table 35: Vehicle deployment across different countries for long haul trucks (I)

	Country where the truck is registered													
Country where the truck operates	**BE**	**BG**	**CZ**	**DK**	**DE**	**EE**	**IE**	**EL**	**ES**	**FR**	**HR**	**IT**	**CY**	**LV**
BE	54%	1.2%	0.3%	0.0%	0.8%	0.4%	0.2%	0.0%	0.4%	1.3%	0.5%	0.1%	0.0%	2.1%
BG	0.0%	48%	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
CZ	0.2%	0.1%	70%	0.0%	0.4%	0.2%	0.0%	0.2%	0.0%	0.0%	1.5%	0.0%	0.0%	0.4%
DK	0.2%	2.2%	0.1%	87%	0.7%	1.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%
DE	8.7%	12%	16%	5.1%	91%	7.9%	0.8%	5.7%	2.0%	1.5%	11%	1.8%	0.1%	17%
EE	0.0%	0.0%	0.0%	0.0%	0.0%	58%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.0%
IE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	80%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EL	0.0%	8.4%	0.0%	0.0%	0.0%	0.0%	0.0%	80%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%
ES	0.3%	4.7%	0.4%	0.0%	0.1%	0.1%	0.2%	0.9%	81%	0.7%	0.6%	0.1%	0.0%	1.4%
FR	30%	7.5%	1.7%	0.8%	2.9%	1.6%	2.1%	2.1%	13%	95%	1.9%	3.3%	0.1%	9.9%
HR	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	43%	0.0%	0.0%	0.0%
IT	0.7%	5.6%	1.2%	0.2%	0.6%	0.3%	0.4%	5.1%	0.9%	0.7%	15%	94%	0.1%	2.7%
CY	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	99%	0.0%
LV	0.0%	0.0%	0.0%	0.0%	0.0%	5.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	36%
LT	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.3%
LU	0.3%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
HU	0.2%	0.6%	1.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%	0.0%	3.9%	0.0%	0.0%	0.1%
MT	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NL	3.8%	1.0%	0.3%	0.1%	1.0%	0.8%	0.2%	0.3%	0.2%	0.1%	0.3%	0.1%	0.0%	1.7%
AT	0.1%	0.8%	3.9%	0.0%	1.5%	0.2%	0.0%	1.6%	0.1%	0.0%	9.3%	0.8%	0.0%	0.9%
PL	0.0%	0.3%	1.4%	0.1%	0.3%	2.8%	0.0%	0.1%	0.0%	0.0%	0.3%	0.0%	0.0%	3.1%
PT	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%
RO	0.0%	3.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SI	0.2%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	12%	0.1%	0.0%	0.0%
SK	0.0%	0.0%	3.3%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.4%	0.0%	0.0%	0.1%
FI	0.0%	0.0%	0.0%	0.0%	0.0%	6.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
SE	0.0%	3.8%	0.3%	6.5%	0.2%	12%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	8.9%
UK	0.8%	0.6%	0.1%	0.2%	0.2%	0.5%	15%	0.1%	0.5%	0.3%	0.2%	0.1%	0.2%	0.7%

Table 36: Vehicle deployment across different countries for long haul trucks (II)

		Country where the truck is registered													
		LT	**LU**	**HU**	**MT**	**NL**	**AT**	**PL**	**PT**	**RO**	**SI**	**SK**	**FI**	**SE**	**UK**
Country where the truck operates	**BE**	3.6%	21%	0.9%	N/A	11%	0.1%	1.5%	0.8%	2.7%	1.2%	1.8%	0.0%	0.0%	0.1%
	BG	0.0%	0.0%	0.1%	N/A	0.0%	0.0%	0.1%	0.0%	0.7%	0.0%	0.1%	0.0%	0.0%	0.0%
	CZ	1.0%	0.0%	2.0%	N/A	0.0%	1.0%	3.2%	0.1%	1.2%	0.8%	12%	0.0%	0.0%	0.0%
	DK	1.8%	0.2%	0.1%	N/A	0.6%	0.0%	0.7%	0.0%	0.6%	0.3%	0.3%	0.0%	0.4%	0.0%
	DE	26%	28%	17%	N/A	31%	24%	28%	4%	17%	22%	21%	0.4%	0.9%	0.1%
	EE	0.7%	0.0%	0.0%	N/A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	IE	0.0%	0.0%	0.0%	N/A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
	EL	0.0%	0.0%	0.1%	N/A	0.0%	0.1%	0.1%	0.0%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%
	ES	4.8%	0.7%	0.9%	N/A	0.1%	0.1%	1.2%	31%	5.3%	1.0%	1.2%	0.0%	0.0%	0.0%
	FR	29%	42%	4.4%	N/A	7.9%	1.0%	7.7%	12%	14%	7.2%	11%	0.0%	0.1%	0.7%
	HR	0.0%	0.0%	0.7%	N/A	0.0%	0.1%	0.1%	0.0%	0.2%	5.7%	0.1%	0.0%	0.0%	0.0%
	IT	6.5%	0.7%	5.8%	N/A	0.3%	5.9%	2.5%	1.0%	5.6%	23%	5.1%	0.0%	0.0%	0.0%
	CY	0.0%	0.0%	0.0%	N/A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LV	1.9%	0.0%	0.0%	N/A	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LT	10%	0.0%	0.0%	N/A	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LU	0.1%	5.8%	0.1%	N/A	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
	HU	0.3%	0.0%	48%	N/A	0.0%	0.7%	0.9%	0.0%	4.7%	2.2%	7.0%	0.0%	0.0%	0.0%
	MT	0.0%	0.0%	0.0%	N/A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	NL	2.0%	1.7%	0.6%	N/A	47%	0.1%	1.2%	0.4%	1.9%	0.7%	0.6%	0.0%	0.1%	0.1%
	AT	2.2%	0.1%	11%	N/A	0.2%	65%	1.8%	0.1%	4.0%	21%	7.9%	0.0%	0.0%	0.0%
	PL	3.7%	0.0%	0.5%	N/A	0.1%	0.0%	47%	0.1%	0.8%	0.6%	2.6%	0.0%	0.0%	0.0%
	PT	0.1%	0.0%	0.0%	N/A	0.0%	0.0%	0.0%	50%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	RO	0.0%	0.0%	2.0%	N/A	0.0%	0.0%	0.3%	0.0%	37%	0.0%	0.5%	0.0%	0.0%	0.0%
	SI	0.1%	0.0%	1.7%	N/A	0.0%	0.5%	0.2%	0.0%	0.7%	13%	0.9%	0.0%	0.0%	0.0%
	SK	0.2%	0.0%	3.1%	N/A	0.0%	0.3%	1.1%	0.0%	0.7%	0.5%	27%	0.0%	0.0%	0.0%
	FI	0.2%	0.0%	0.0%	N/A	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	96%	0.1%	0.0%
	SE	3.1%	0.0%	0.2%	N/A	0.7%	0.2%	1.4%	0.0%	0.5%	0.6%	0.5%	3.8%	98%	0.0%
	UK	2.2%	0.3%	1.0%	N/A	1.2%	0.1%	1.1%	0.8%	2.0%	0.7%	0.9%	0.0%	0.0%	98%

E Component cost references

The following references have been consulted to support the TCO calculations in section 4.

Table 37: References used for component cost estimates in vehicle cost model.

Component	Reference
Diesel engine	Zyl van, S. et al. 2021. Aanzet tot een analysekader betreffende de ingroei en opschaling van elektrische bestel en vrachtvoertuigen in de Nederlandse vloot tot 2040. TNO R11987
Diesel engine	Roland Berger. 2020. Fuel Cells Hydrogen Trucks: Heavy-Duty's High Performance Green Solution. Study Report. FCH JU
Diesel engine	Den Boer et al. 2013. An Overview of State-of-the-Art Technologies and Their Potential. CE Delft.
Electric drivetrain	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
Fuel Cell	Den Boer et al. 2013. An Overview of State-of-the-Art Technologies and Their Potential. CE Delft.
Fuel Cell	Fulton, L. and Miller, M. 2015. Strategies for Transitioning to Low-Carbon Emission Trucks in the United States
Fuel Cell	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
Fuel Cell	Roland Berger. 2020. Fuel Cells Hydrogen Trucks: Heavy-Duty's High Performance Green Solution. Study Report. FCH JU
Fuel Cell	Noll, B. et al. 2022. Analyzing the competitiveness of low carbon drive-technologies in road freight. A total cost of ownership analysis in Europe
Fuel Cell	Hunter, C. et al. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. NREL
Fuel Cell	Burham, A. et al. 2021. Comprehensive Total Cost of Ownership Quantifications for Vehicles with Different Size Classes and Powertrains. Argonne National Laboratory
Fuel Cell	Burke, A. et al. 2020. Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040. National Center for Sustainable Transportation | UC Davis
Fuel Cell	James, B, D. 2021. 2021 DOE Hydrogen and Fuel Cells Program Review Presentation. Strategic Analysis
Fuel Cell	AC UK, 2021. Fuel Cell Roadmap 2020. Automotive Council UK | Advanced Propulsion Centre UK
Fuel Cell	James, B. D. et al. 2018. Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications 2018 Update. Strategic Analysis
Fuel Cell	CH2M HILL Canada. 2018. Regional Express Rail Program Hydrail Feasibility Study Report.

Hydrogen storage tank	Ricardo. 2016. Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves. Service request 4 to LDV Emissions Framework Contract.
Hydrogen storage tank	Roland Berger. 2020. Fuel Cells Hydrogen Trucks: Heavy-Duty's High Performance Green Solution. Study Report. FCH JU
Diesel tank	Fries, M. et al. 2017. An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Costs of Ownership Update 2017.
Diesel tank	Fulton, L. and Miller, M. 2015. Strategies for Transitioning to Low-Carbon Emission Trucks in the United States
On-Board charger	Fries, M. et al. 2017. An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Costs of Ownership Update 2017.
On-Board charger	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
Exhaust aftertreatment system	Fries, M. et al. 2017. An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Costs of Ownership Update 2017.
Control units and BMU	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
High voltage Air compressor	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
High voltage Steering pump	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
Heater/airconditioning compressor	Ricardo. 2021. E-Truck Virtual Teardown Study. ICCT
Glider	Zyl van, S. et al. 2021. Aanzet tot een analysekader betreffende de ingroei en opschaling van elektrische bestel en vrachtvoertuigen in de Nederlandse vloot tot 2040. TNO R11987
Glider	Roland Berger. 2020. Fuel Cells Hydrogen Trucks: Heavy-Duty's High Performance Green Solution. Study Report. FCH JU
Glider	Moultak, M. et al. 2017. Transitining to Zero-Emission Heavy Duty Freight Vehicles. ICCT
Glider	Den Boer et al. 2013. An Overview of State-of-the-Art Technologies and Their Potential. CE Delft.
Glider	Basma, H. et al. 2021. Total Cost of Ownership For Tractor Trailers in Europe: Battery Electric vs. Diesel. ICCT
Glider	Kleiner, F., Friedrich H.E. 2017. Development of a Transport Application Based Cost Model for the assessment of future commercial vehicle concepts. European Battery, Hybrid and Fuel Cell Electric Vehicle Congress.
Trailer	Moultak, M. et al. 2017. Transitining to Zero-Emission Heavy Duty Freight Vehicles. ICCT
Trailer	Meszler, D. et al. 2018. European Heavy-Duty Vehicles: Cost Effectiveness of Fuel-Efficiency Technologies for Long Haul Tractor-Trailers in the 2025-2030 Timeframe. ICCT

Trailer	Basma, H. et al. 2021. Total Cost of Ownership For Tractor Trailers in Europe: Battery Electric vs. Diesel. ICCT
Mark-up	Sharpe, B., Basma, H. A meta-study of purchase costs for zero-emission trucks. ICCT
Energy efficiency technologies	Verbeek, M. et al. 2018. Assessment With Respect to the EU HDV CO2 Legislation. TNO P10214
HICP index	EC. n.d. Statistics | Eurostat
Battery	BNEF. 2021. 2021 Lithium-Ion Battery Price Survey

F Vehicle price breakdowns

This appendix shows the detailed results for the breakdown of the pre-tax retail prices for the four vehicle categories studied in this report, as determined in section 4.2.9.

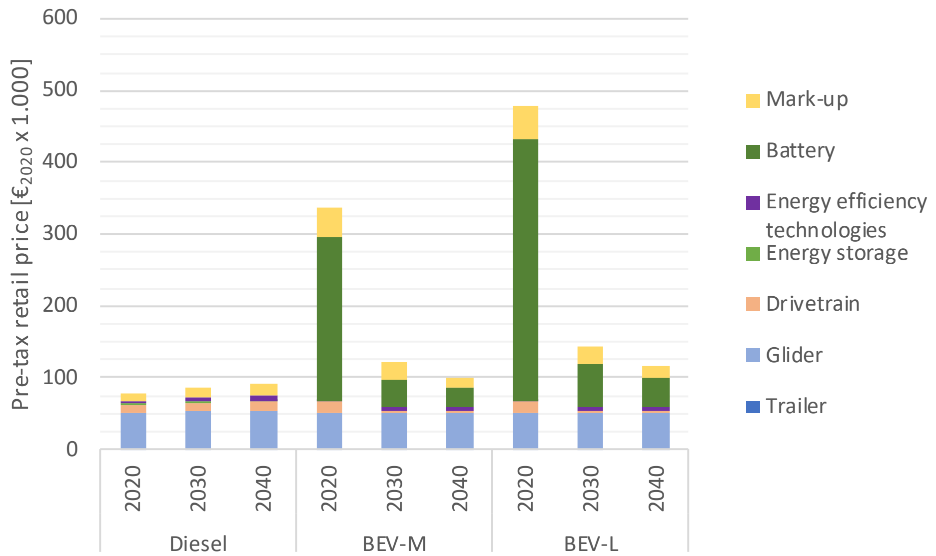

Figure 43: Pre-tax retail price breakdown for rigid urban truck

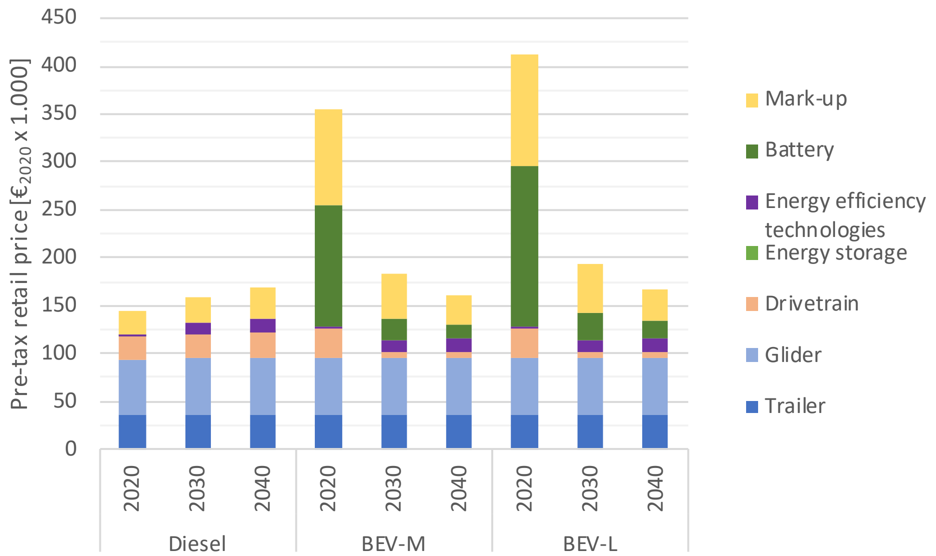

Figure 44: Pre-tax retail price breakdown for articulated regional truck

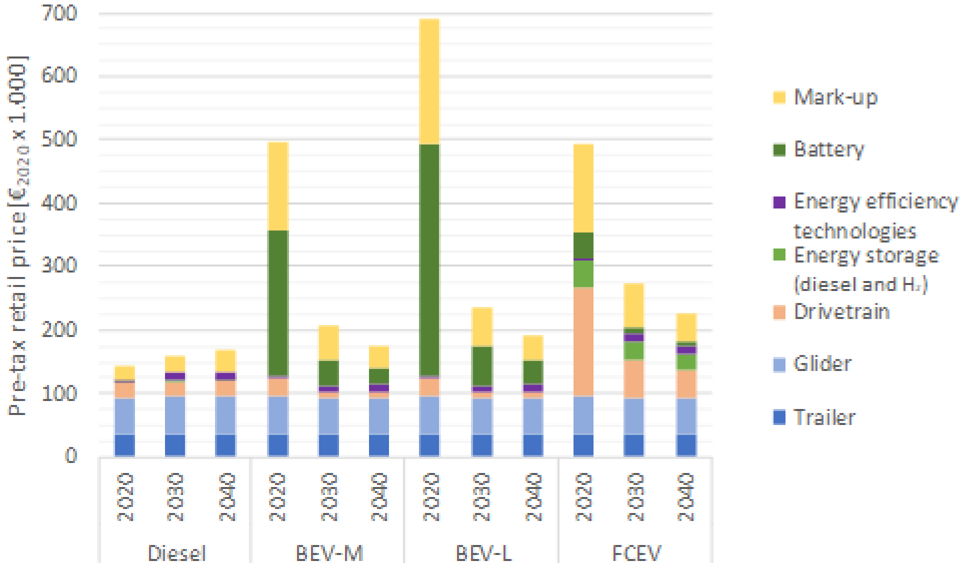

Figure 45: Pre-tax retail price breakdown for the articulated long haul truck including trailer.

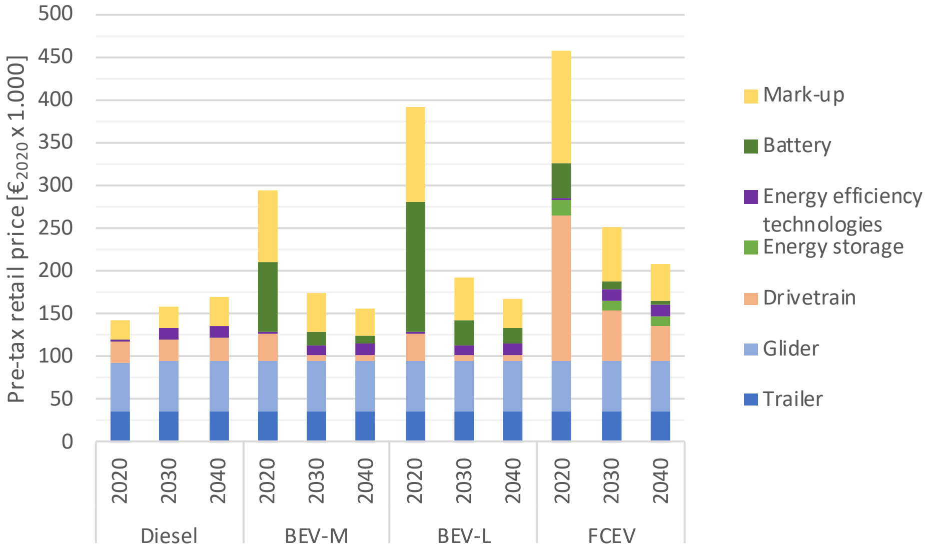

Figure 46: Pre-tax retail price breakdown for articulated construction truck

G Energy prices

The following tables contain the date on the country-specific price estimations for 2020, 2030 and 2040. 2020 electricity prices are obtained from Eurostat.

Table 38: Diesel price assumptions per country in €/litre (excl. VAT, incl. excise duty and applicable fuel rebates).

Country	2020 (based on 2010-2020 average)	2030	2040
Austria	1.00	1.12	1.17
Belgium	0.98	1.11	1.16
Bulgaria	0.95	1.08	1.13
Croatia	0.99	1.11	1.16
Cyprus	1.05	1.18	1.24
Czech Republic	0.98	1.11	1.16
Denmark	1.10	1.24	1.30
Estonia	0.97	1.09	1.15
Finland	1.17	1.31	1.36
France	1.02	1.13	1.18
Germany	1.08	1.20	1.25
Greece	0.69	0.83	0.89
Hungary	0.94	1.07	1.12
Ireland	1.04	1.17	1.22
Italy	1.03	1.15	1.21
Latvia	1.03	1.15	1.20
Lithuania	1.00	1.12	1.18
Luxembourg	1.01	1.14	1.19
Malta	1.05	1.18	1.24
Netherlands	1.14	1.26	1.31
Poland	0.93	1.05	1.11
Portugal	1.15	1.28	1.34
Romania	0.92	1.05	1.10
Slovakia	1.00	1.13	1.18
Slovenia	1.04	1.15	1.20
Spain	0.97	1.09	1.15
Sweden	1.13	1.27	1.32
United Kingdom	1.17	1.28	1.33

Table 39: End user public fast charging price assumption per country including infrastructure costs in €/kWh (excl. VAT and recoverable taxes and levies) obtained from (Kippelt & Burges, 2022) .

Country	**2020 (based on 2010-2020 average)**	**2030**	**2040**
Austria	0.19	0.22	0.18
Belgium	0.19	0.23	0.19
Bulgaria	0.16	0.20	0.16
Croatia	0.18	0.21	0.17
Cyprus	0.25	0.27	0.22
Czech Republic	0.17	0.20	0.15
Denmark	0.17	0.20	0.15
Estonia	0.17	0.21	0.17
Finland	0.15	0.19	0.14
France	0.17	0.20	0.16
Germany	0.23	0.27	0.23
Greece	0.20	0.23	0.18
Hungary	0.17	0.21	0.18
Ireland	0.21	0.24	0.20
Italy	0.24	0.28	0.23
Latvia	0.19	0.24	0.20
Lithuania	0.18	0.23	0.19
Luxembourg	0.17	0.21	0.18
Malta	0.23	0.29	0.24
Netherlands	0.17	0.21	0.17
Poland	0.17	0.21	0.17
Portugal	0.19	0.23	0.18
Romania	0.17	0.21	0.17
Slovakia	0.20	0.24	0.19
Slovenia	0.17	0.20	0.17
Spain	0.19	0.22	0.16
Sweden	0.15	0.18	0.13
United Kingdom	0.21	0.24	0.19

Table 40: End user private charging price assumption per country including infrastructure costs in €/kWh (excl. VAT and recoverable taxes and levies) obtained from (Kippelt & Burges, 2022)

Country	**2020 (based on 2010-2020 average)**	**2030**	**2040**
Austria	0.15	0.16	0.17
Belgium	0.16	0.17	0.18
Bulgaria	0.13	0.14	0.15
Croatia	0.14	0.16	0.15
Cyprus	0.21	0.22	0.21
Czech Republic	0.13	0.14	0.14
Denmark	0.13	0.14	0.14
Estonia	0.13	0.15	0.15
Finland	0.12	0.13	0.13
France	0.14	0.14	0.15
Germany	0.20	0.21	0.22
Greece	0.16	0.17	0.16
Hungary	0.14	0.15	0.16
Ireland	0.18	0.18	0.19
Italy	0.21	0.22	0.22
Latvia	0.16	0.18	0.19
Lithuania	0.15	0.17	0.18
Luxembourg	0.14	0.15	0.16
Malta	0.20	0.23	0.22
Netherlands	0.14	0.15	0.16
Poland	0.14	0.15	0.16
Portugal	0.16	0.17	0.16
Romania	0.13	0.15	0.15
Slovakia	0.17	0.18	0.18
Slovenia	0.14	0.15	0.16
Spain	0.16	0.16	0.15
Sweden	0.12	0.12	0.12
United Kingdom	0.17	0.18	0.18

Table 41: End user renewable hydrogen price assumptions per country including infrastructure costs in €/kg (excl. VAT, excise duty does not apply).

Country	2020	2030	2040
Austria	8.7	6.9	5.4
Belgium	9.5	7.5	6.0
Bulgaria	8.5	6.1	4.6
Croatia	7.8	5.5	4.0
Cyprus	11.5	8.7	6.9
Czech Republic	8.5	6.7	5.2
Denmark	10.2	8.2	6.6
Estonia	8.9	7.1	5.6
Finland	8.2	6.4	4.9
France	9.0	7.1	5.5
Germany	11.2	9.0	7.5
Greece	8.3	6.1	4.7
Hungary	9.6	7.0	5.4
Ireland	7.6	6.2	4.8
Italy	11.7	8.6	7.0
Latvia	11.0	8.6	7.0
Lithuania	9.1	7.2	5.7
Luxembourg	10.1	6.9	5.3
Malta	8.3	6.1	4.7
Netherlands	8.3	6.6	5.1
Poland	8.1	6.4	4.9
Portugal	9.3	7.1	5.6
Romania	9.4	7.3	5.8
Slovakia	11.6	8.7	7.1
Slovenia	9.8	6.9	5.3
Spain	8.7	7.0	5.5
Sweden	7.3	5.8	4.4
United Kingdom	7.6	6.2	4.8

H Market-driven uptake scenario per country

The table shows the country-specific results of the market-driven uptake scenario for the years 2025, 2030 and 2040. This is the outcome of the calculations performed in section 6.2.

Table 42: ZE uptake potential (BEV + FCEV) for all individual EU+UK countries.

Country	Vehicle type	2025	2030	2040
Belgium	Rigid Urban	94%	100%	100%
	Articulated Regional	84%	99%	100%
	Articulated Long Haul	41%	100%	100%
	Articulated Construction	75%	99%	100%
Bulgaria	Rigid Urban	95%	100%	100%
	Articulated Regional	87%	99%	100%
	Articulated Long Haul	44%	100%	100%
	Articulated Construction	90%	99%	100%
Czech Republic	Rigid Urban	97%	100%	100%
	Articulated Regional	94%	100%	100%
	Articulated Long Haul	55%	99%	100%
	Articulated Construction	94%	99%	100%
Denmark	Rigid Urban	94%	100%	100%
	Articulated Regional	95%	100%	100%
	Articulated Long Haul	99%	100%	100%
	Articulated Construction	94%	99%	100%
Germany	Rigid Urban	94%	100%	100%
	Articulated Regional	82%	99%	100%
	Articulated Long Haul	14%	100%	100%
	Articulated Construction	72%	98%	100%
Estonia	Rigid Urban	96%	100%	100%
	Articulated Regional	92%	100%	100%
	Articulated Long Haul	62%	98%	98%
	Articulated Construction	93%	99%	100%
Ireland	Rigid Urban	96%	100%	100%
	Articulated Regional	92%	99%	100%
	Articulated Long Haul	40%	99%	100%
	Articulated Construction	92%	99%	100%
Greece	Rigid Urban	92%	100%	100%
	Articulated Regional	0%	99%	100%
	Articulated Long Haul	0%	98%	99%
	Articulated Construction	23%	98%	100%

Country	Vehicle type	2025	2030	2040
Spain	Rigid Urban	96%	100%	100%
	Articulated Regional	92%	100%	100%
	Articulated Long Haul	48%	99%	100%
	Articulated Construction	93%	99%	100%
France	Rigid Urban	94%	100%	100%
	Articulated Regional	93%	100%	100%
	Articulated Long Haul	77%	100%	100%
	Articulated Construction	89%	99%	100%
Croatia	Rigid Urban	96%	100%	100%
	Articulated Regional	95%	100%	100%
	Articulated Long Haul	27%	97%	97%
	Articulated Construction	94%	99%	100%
Italy	Rigid Urban	97%	100%	100%
	Articulated Regional	89%	100%	100%
	Articulated Long Haul	0%	98%	98%
	Articulated Construction	83%	98%	100%
Cyprus	Rigid Urban	94%	100%	100%
	Articulated Regional	82%	99%	100%
	Articulated Long Haul	0%	100%	100%
	Articulated Construction	73%	98%	100%
Latvia	Rigid Urban	96%	100%	100%
	Articulated Regional	90%	99%	100%
	Articulated Long Haul	43%	99%	99%
	Articulated Construction	93%	99%	100%
Lithuania	Rigid Urban	96%	100%	100%
	Articulated Regional	88%	99%	100%
	Articulated Long Haul	43%	99%	100%
	Articulated Construction	93%	99%	100%
Luxembourg	Rigid Urban	94%	100%	100%
	Articulated Regional	92%	100%	100%
	Articulated Long Haul	50%	100%	100%
	Articulated Construction	89%	99%	100%
Hungary	Rigid Urban	97%	100%	100%
	Articulated Regional	92%	100%	100%
	Articulated Long Haul	31%	99%	99%
	Articulated Construction	94%	99%	100%
Malta	Rigid Urban	94%	100%	100%
	Articulated Regional	74%	99%	100%
	Articulated Long Haul	0%	100%	100%
	Articulated Construction	72%	96%	100%

Country	Vehicle type	2025	2030	2040
Netherlands	Rigid Urban	94%	100%	100%
	Articulated Regional	92%	99%	100%
	Articulated Long Haul	74%	100%	100%
	Articulated Construction	93%	99%	100%
United Kingdom	Rigid Urban	96%	100%	100%
	Articulated Regional	95%	100%	100%
	Articulated Long Haul	76%	99%	100%
	Articulated Construction	92%	99%	100%
Austria	Rigid Urban	93%	100%	100%
	Articulated Regional	86%	99%	100%
	Articulated Long Haul	34%	100%	100%
	Articulated Construction	88%	98%	100%
Poland	Rigid Urban	96%	100%	100%
	Articulated Regional	93%	100%	100%
	Articulated Long Haul	30%	99%	99%
	Articulated Construction	92%	99%	100%
Portugal	Rigid Urban	97%	100%	100%
	Articulated Regional	97%	100%	100%
	Articulated Long Haul	69%	99%	99%
	Articulated Construction	95%	99%	100%
Romania	Rigid Urban	97%	100%	100%
	Articulated Regional	96%	100%	100%
	Articulated Long Haul	22%	96%	96%
	Articulated Construction	95%	99%	100%
Slovenia	Rigid Urban	95%	100%	100%
	Articulated Regional	92%	99%	100%
	Articulated Long Haul	25%	100%	100%
	Articulated Construction	92%	99%	100%
Finland	Rigid Urban	95%	100%	100%
	Articulated Regional	97%	100%	100%
	Articulated Long Haul	96%	98%	100%
	Articulated Construction	95%	99%	100%
Sweden	Rigid Urban	94%	100%	100%
	Articulated Regional	96%	100%	100%
	Articulated Long Haul	99%	100%	100%
	Articulated Construction	94%	99%	100%
Slovakia	Rigid Urban	96%	100%	100%
	Articulated Regional	88%	100%	100%
	Articulated Long Haul	30%	99%	99%
	Articulated Construction	94%	99%	100%

Country	**Vehicle type**	**2025**	**2030**	**2040**
EU+UK	Rigid Urban	95%	100%	100%
	Articulated Regional	91%	99%	100%
	Articulated Long Haul	59%	100%	100%
	Articulated Construction	92%	99%	100%

I Sensitivity analyses

As discussed in section 6.3, in this appendix the detailed results of the sensitivity analyses are provided. The results are grouped into different sets of sensitivities in the form of ‘cost related parameter scenarios’, and ‘deployment related parameter scenarios’.

I.1 Robustness of results

The uptake potential as determined in this study is based on the TCO and applicability of zero-emission trucks. In cases where the difference between the TCO of diesel trucks and zero-emission equivalents is small, slight changes in costs or deployment may have a significant impact on the results. In cases where the TCO difference is small for a large group of vehicles, this would have a very large effect on the uptake potential. The ‘robustness’ of the determined uptake potential is therefore also assessed.

This robustness is defined as the share of the uptake potential for which the TCO advantage of zero-emission trucks is greater than 10% compared to diesel trucks. Figure 47 shows a heatmap where the colours indicate the difference between the TCO of the most cost-effective zero-emission vehicle compared to the diesel counterpart. The area which colours lighter than dark blue is seen as robust, having a more than 10% TCO benefit. The applicability restricts the average daily mileage that can be covered, above 625 km/day no ZE long haul trucks are applicable. Note that in this example the EU+UK average energy prices have been used because it is not feasible for this analysis to aggregate from a country-specific level.

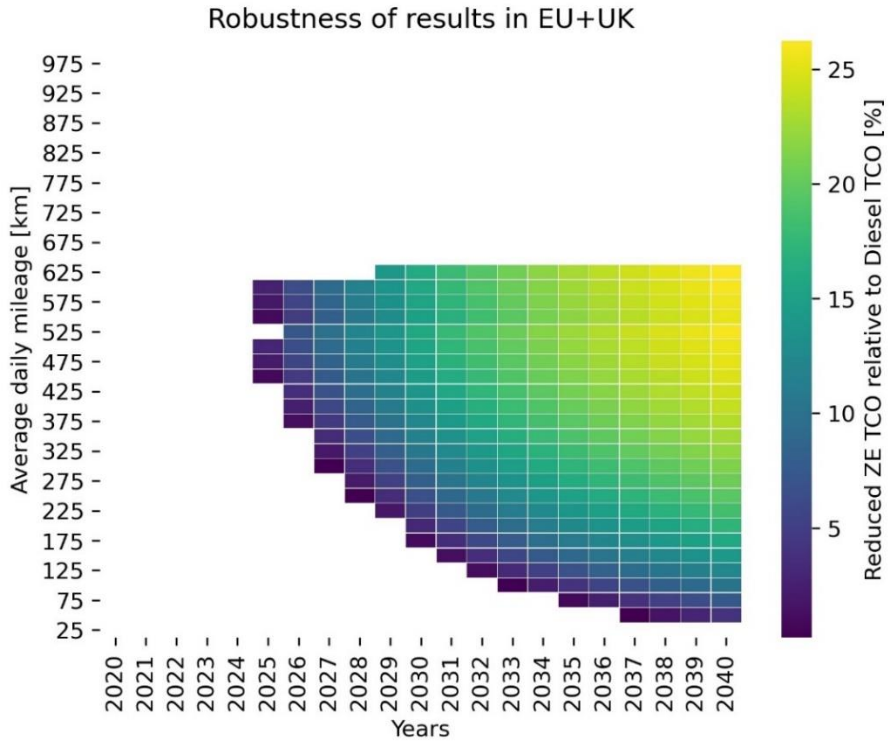

Figure 47: Relative TCO differential for the ZE long haul truck compared to the diesel reference using EU+UK average energy prices and range requirements.

I.2 Cost-related parameter scenarios

I.2.1 Higher battery prices

When prices of batteries do not come down as fast as assumed in the main scenario, the costs of BEVs and FCEVs will consequently be higher. This could result in a lower and/or slower uptake of such vehicles. To assess the potential impact of lower battery price reduction on the uptake of zero-emission trucks, the alternative battery price trajectory as explained in section 4.2.1 is used (orange line in Figure 9). According to this trajectory, assumed battery prices are 31% higher in 2030. Figure 48 shows that the higher battery prices will delay the uptake potential by two to three years at most, resulting in a similar uptake potential as for the central scenario in the long term. The dotted lines present the same scenarios if a robustness criterion is applied as a 10% TCO benefit, indicated as ‘10% margin’. Comparing the 10% margin curves (dotted blue and green lines), the uptake trajectories are delayed similarly as for the sensitivity scenario without 10% margin. Between the central scenario (solid blue line) and the 10% margin (dotted blue line) a delay of up to 4 years in the uptake potential can be seen, depending on the vehicle type. Note that these lines remain the same for all of the figures in this appendix.

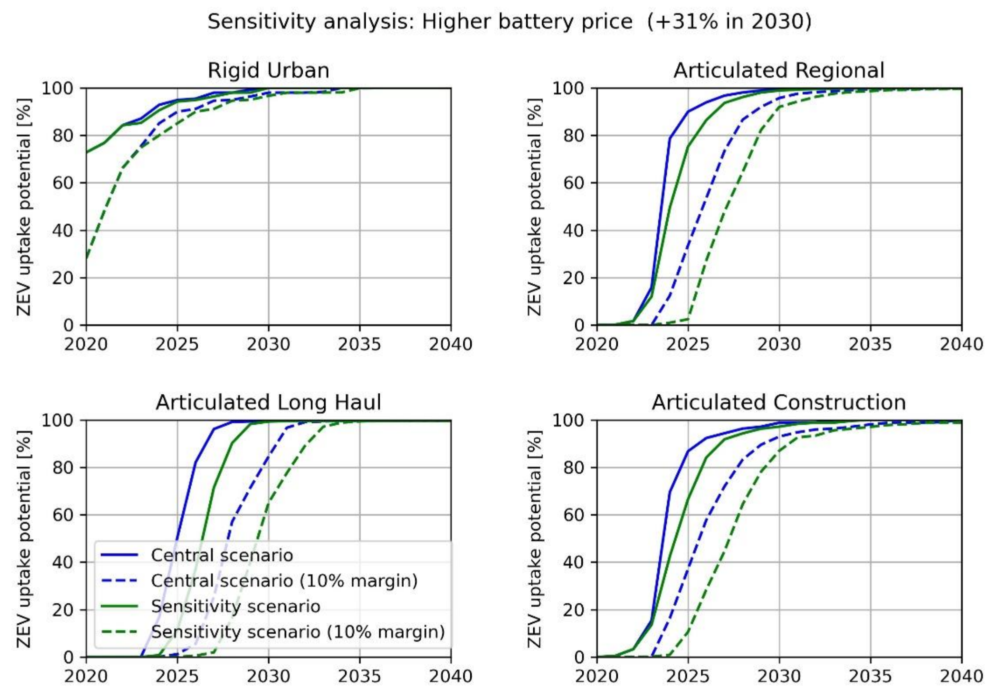

Figure 48: Impact of the 'higher battery price' scenario on ZEV uptake potentials for the EU+UK.

I.2.2 *Lower diesel prices*

In section 4.3.1, two diesel price projection scenarios are shown based on the World Energy Outlook 2021 (IEA, 2021). These scenarios are known as 'stated policies' and 'announced pledges'. As explained in section 4.3.1, the 'stated policies' scenario is used for the central scenario. To assess the sensitivity of the uptake potential of zero-emission trucks to lower diesel prices, the 'announced pledges' scenario is used in this sensitivity analysis. The price difference between these scenarios grows to a 12% lower diesel price by 2030 and 17% by 2040. The uptake potential in that case follows a similar trajectory as in the central scenario but is delayed by about 1 year. If the robustness criterion of a 10% TCO benefit is applied, the delay increases to 2.5 years maximum.

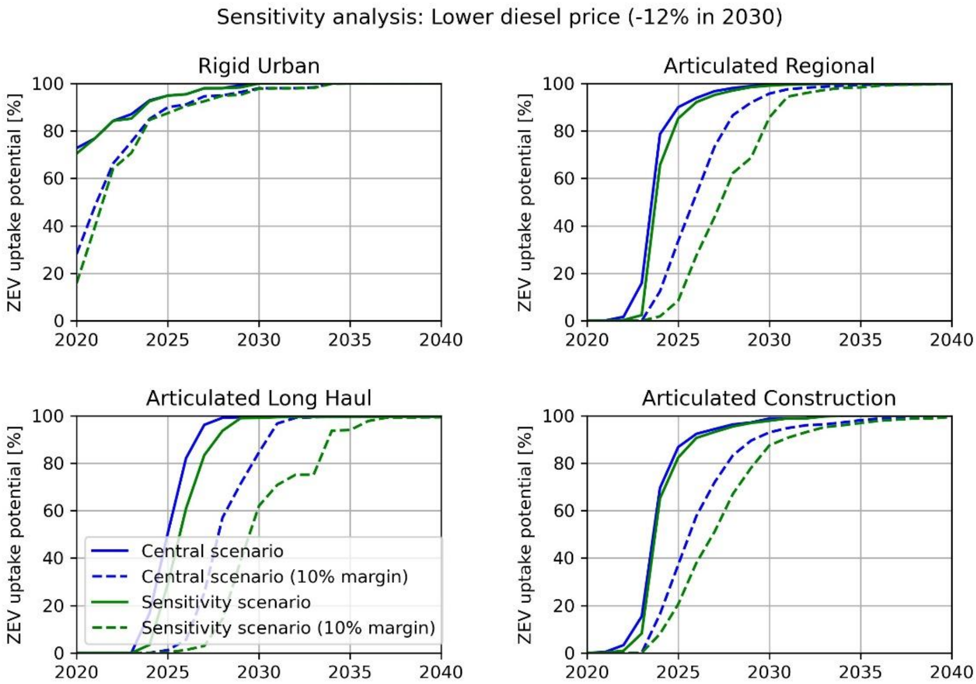

Figure 49: Impact of the 'lower diesel fuel price' scenario on ZEV uptake potentials for the EU+UK.

I.2.3 Lower renewable hydrogen prices

The development of the hydrogen price is rather uncertain. Therefore a sensitivity analysis is performed with a lower hydrogen price. The effect of higher hydrogen prices is not relevant due to the limited cost competitiveness of FCEV in the central scenario. The lower hydrogen prices are based on the optimistic hydrogen price scenario in (ICCT, 2022) and are shown in Figure 50.

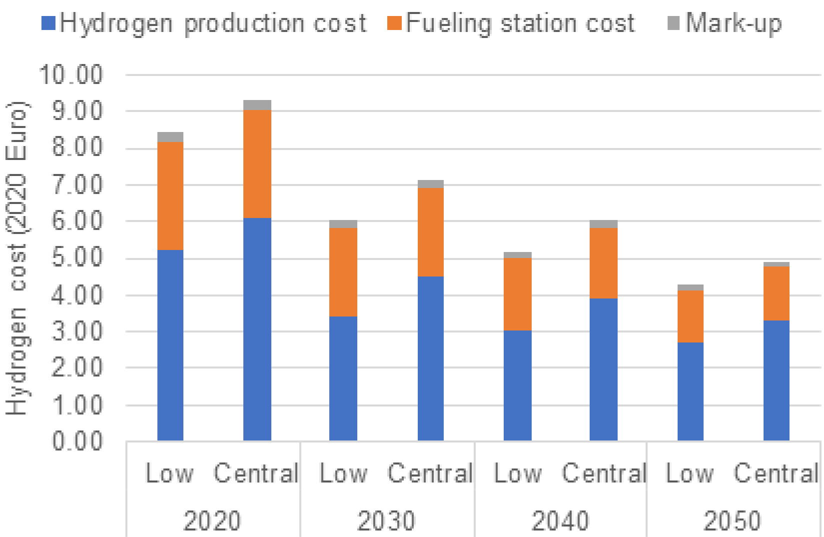

Figure 50: Assumed hydrogen prices in the low and central scenario

Figure 51 shows that the lower hydrogen price does result in any difference compared to the central scenario, the blue and green lines overlap completely.

Even at this lower hydrogen price, the TCO of FCEVs remains higher than that of BEVs. Since BEVs will be able to cover close to all of the types of deployment assessed in this study, there is no techno-economic uptake potential for FCEVs for these vehicle categories.

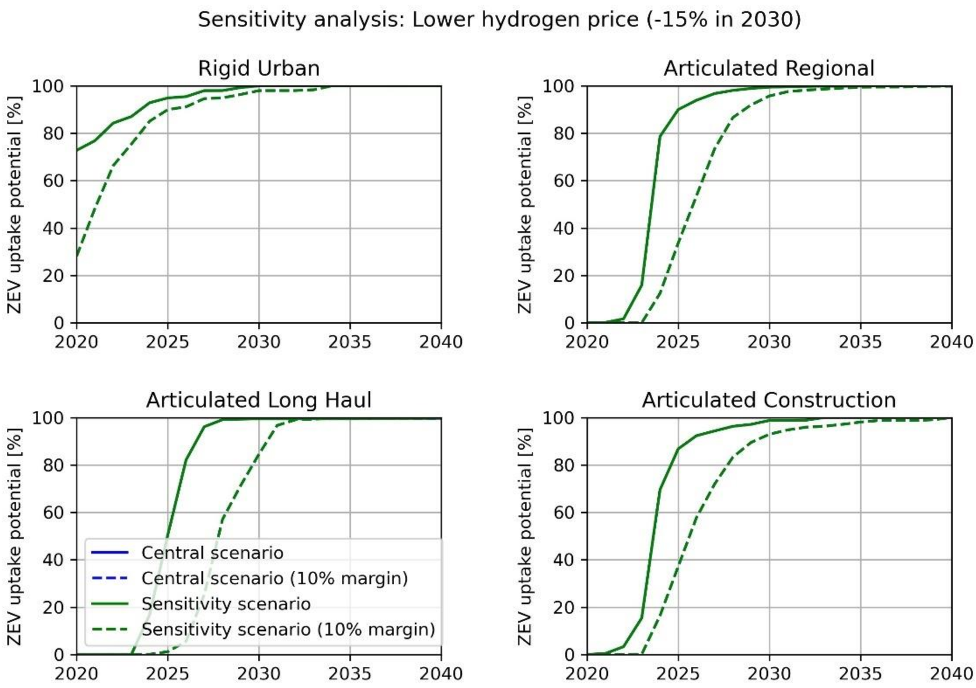

Figure 51: Impact of the ‘lower hydrogen price’ scenario on ZEV uptake potentials for the EU+UK.

I.2.4 Higher and lower fuel cell prices

Fuel cell system price projections vary significantly between the many literature sources assessed. To assess the effects of different fuel cell system prices on the uptake potential of FCEVs, two additional scenarios are analysed. One with lower and one with higher fuel cell prices than assumed in the main scenario. These alternative fuel cell price projections were already shown in Figure 10 of section 4.2.3.

At higher fuel cell cost, these drivetrains become less cost effective. Since the uptake potential is close to 0% in the central scenario, a higher fuel cell cost does not affect the uptake potential pace. Even at lower fuel cell costs, BEVs are a more cost-effective technology and therefore this uptake potential is not affected.

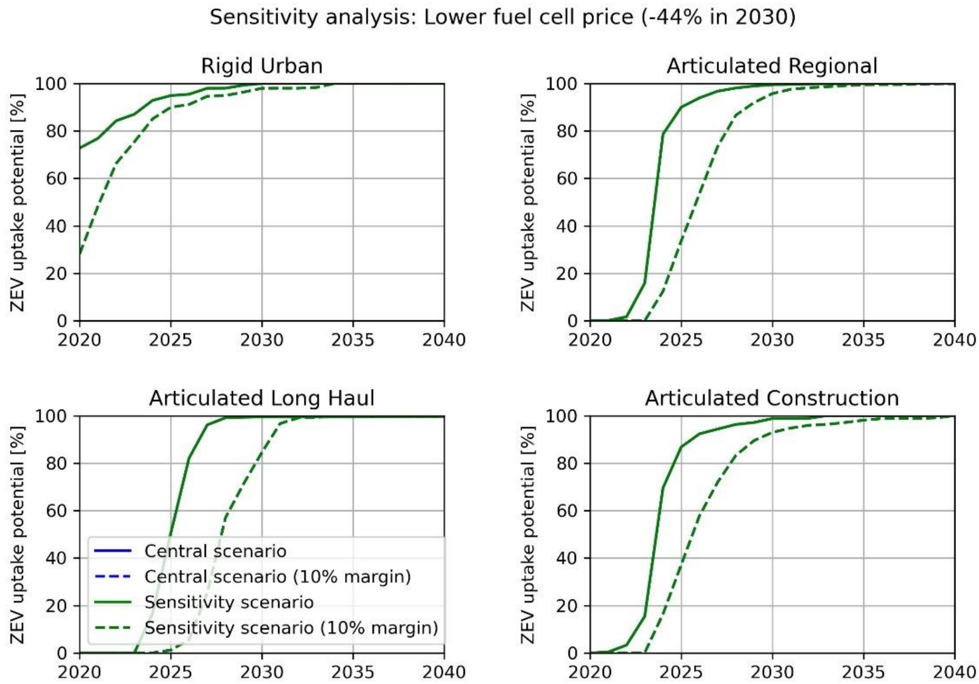

Figure 52: Impact of the 'lower fuel cell system price' scenario on ZEV uptake potentials for the EU+UK.

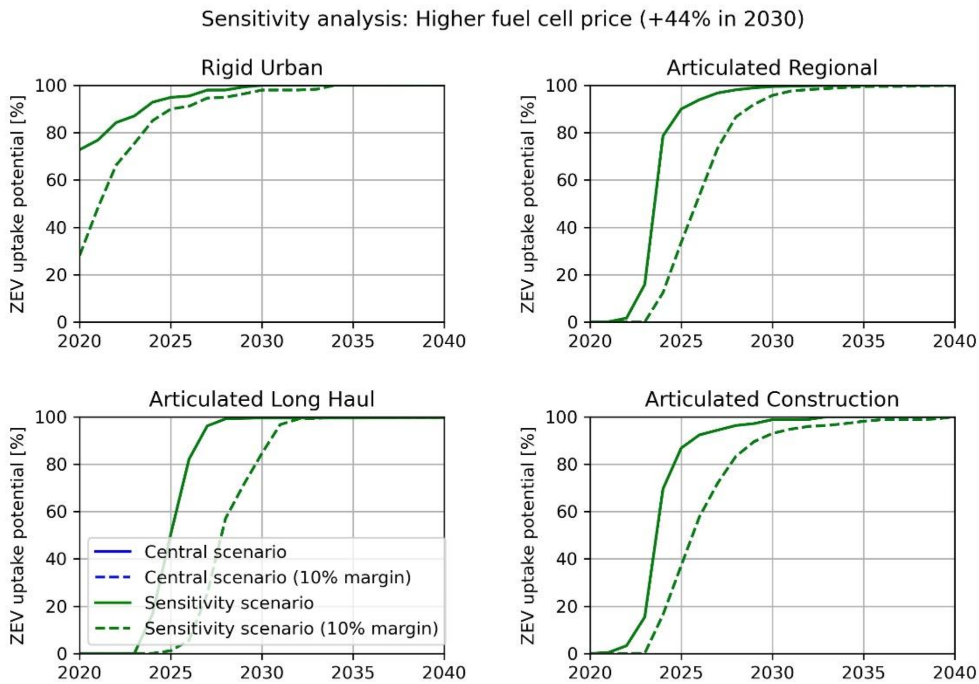

Figure 53: Impact of the 'higher fuel cell system price' scenario on ZEV uptake potentials for the EU+UK.

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I.2.5 Higher fast charging infrastructure costs

In this sensitivity analysis it is assumed that the costs for fast charging infrastructure are higher than in the central scenario. At 0.15 €/kWh, the costs for infrastructure are 56% and 173% higher in 2030 and 2040, respectively, compared to the central scenario. This results in 26% and 57% higher electricity prices in 2030 and 2040, respectively. There is almost no effect (<1% before 2030) on the uptake potential compared to the central scenario.

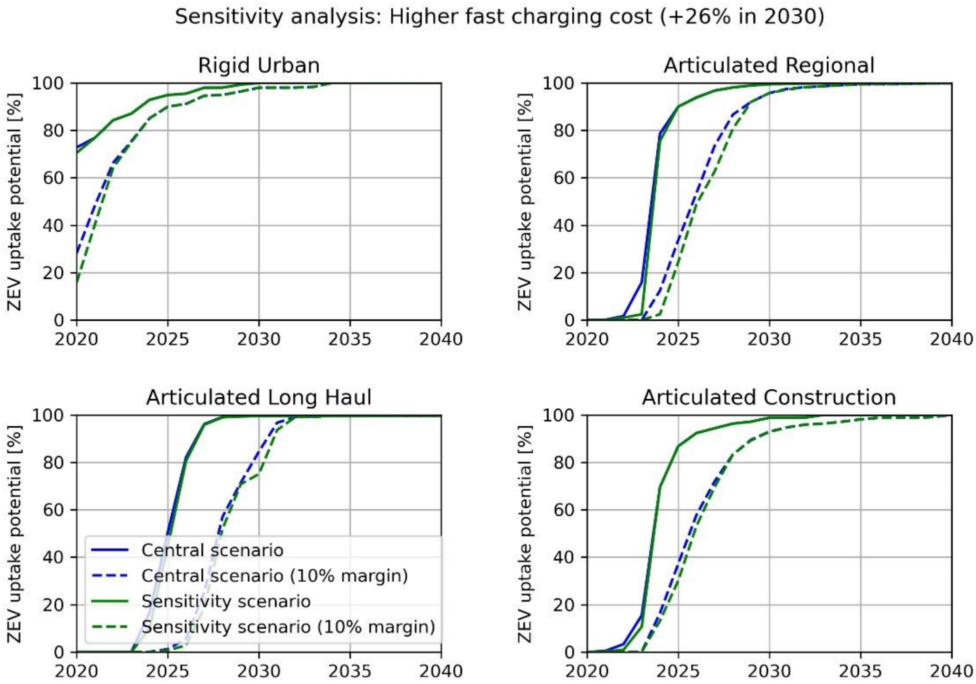

Figure 54: Impact of the ‘higher fast charging infrastructure price’ scenario on ZEV uptake potentials for the EU+UK.

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I.2.6 Summary for cost-related parameter variations

In the table below the differences in ZEV uptake potential for various cost-related parameter variation scenarios are listed relative to the central scenario. A distinction is made between the BEVs and FCEVs such that the effect on both can be assessed separately.

Table 43: Summary of the impacts on ZE uptake potential for every sensitivity scenario for the EU+UK..

Scenario	Vehicle type	2030		2040	
		BEV	FCEV	BEV	FCEV
Central scenario	Rigid Urban	100.0%		100.0%	
	Articulated Regional	99.4%		100.0%	
	Articulated Long Haul	99.5%	0.0%	99.6%	0.1%
	Articulated Construction	98.8%	0.0%	100.0%	0.0%
Lower hydrogen price (-15% in 2030)	Rigid Urban	0%		0%	
	Articulated Regional	0%		0%	
	Articulated Long Haul	0%	0.0%	0%	0.1%
	Articulated Construction	0%	0.0%	0%	0.0%
Lower diesel price (-12% in 2030)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	-0.3%		0.0%	
	Articulated Long Haul	-0.4%	0.0%	0.0%	0.0%
	Articulated Construction	-0.9%	0.0%	0.0%	0.0%
Higher battery price (+31% in 2030)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	-0.5%		0.0%	
	Articulated Long Haul	-0.2%	0.0%	0.0%	0.0%
	Articulated Construction	-1.6%	0.0%	0.0%	0.0%
Higher fast charging cost (+26% in 2030)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	0.0%	0.0%	0.0%	0.0%
	Articulated Construction	0.0%	0.0%	0.0%	0.0%
Higher fuel cell price (+44% in 2030)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	0.0%	0.0%	0.0%	0.0%
	Articulated Construction	0.0%	0.0%	0.0%	0.0%
Lower fuel cell price (-44% in 2030)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	0.0%	0.0%	0.0%	0.0%
	Articulated Construction	0.0%	0.0%	0.0%	0.0%

I.3 Deployment-related parameter scenarios

I.3.1 Higher variation in daily distance

As explained in section 5.4 the current (diesel) fleet is not optimized for range-limited vehicles, therefore it is not completely representative for a fleet with a high share of BEVs. Especially larger companies can reduce the daily spread in vehicle mileages, increasing the uptake potential of battery electric vehicles. In the baseline scenario the standard deviation is reduced with an optimisation factor of 30%. The effect of that assumption is quantified using this scenario.

Eliminating the daily distance optimisation factor hardly affects the uptake potential for the articulated regional delivery truck and articulated long haul truck. However, for the rigid urban delivery truck and the articulated construction truck, the maximum uptake potential changes to respectively 80% and 95% compared to 100% in the central scenario. This means that the battery capacity of the modelled vehicles is too small to cover more than 90% of the trips.

In case the daily distance variation cannot be improved to the current situation, the rigid urban delivery truck and the articulated construction truck would thus have to be fitted with larger batteries than assumed in this study in order to achieve the uptake potentials estimated for the central scenario.

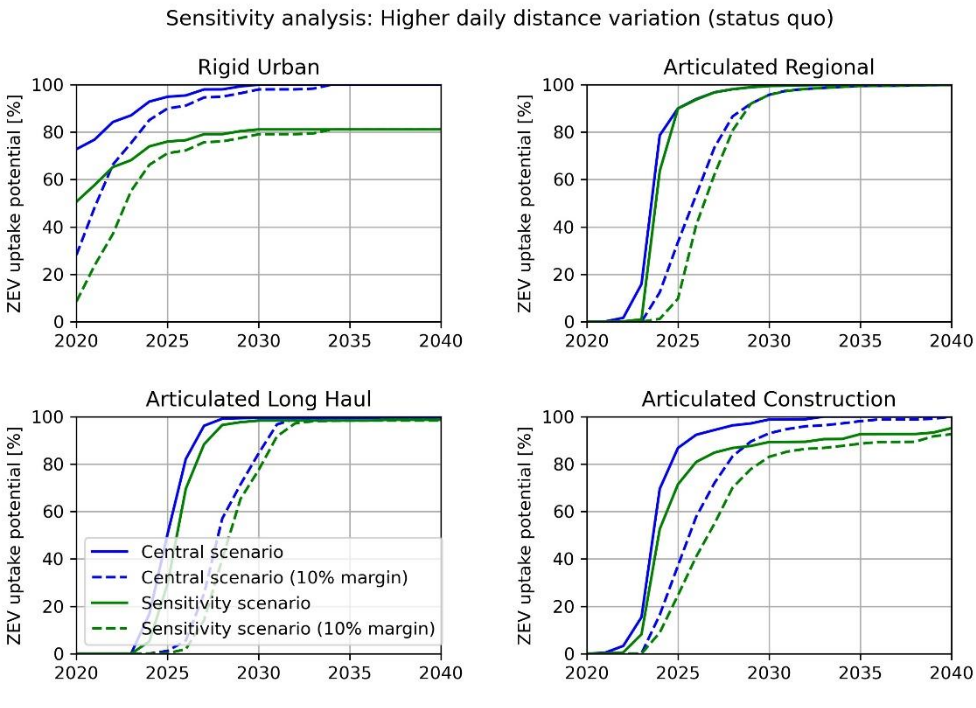

Figure 55: Impact of the 'optimisation factor = 1' (status quo) scenario on ZEV uptake potentials for the EU+UK.

I.3.2 *Applicability*

In the previous section it was made clear that the daily variation in trip distance has an impact on the BEV (and potentially FCEV) uptake potential. The maximum daily range that can be electrified is affected by this parameter. The effect on the ZE-uptake potential is explored by running the main scenario with 80% and 95% applicability instead of 90% as assumed in the central scenario. As explained in section 5.5 an applicability of 90% means that 90% of the daily mileages can be covered by one full battery charge plus 45 minutes of fast charging.

As shown in the figure below, requiring only 80% of daily distances to be executable with a BEV hardly affects the uptake potential.

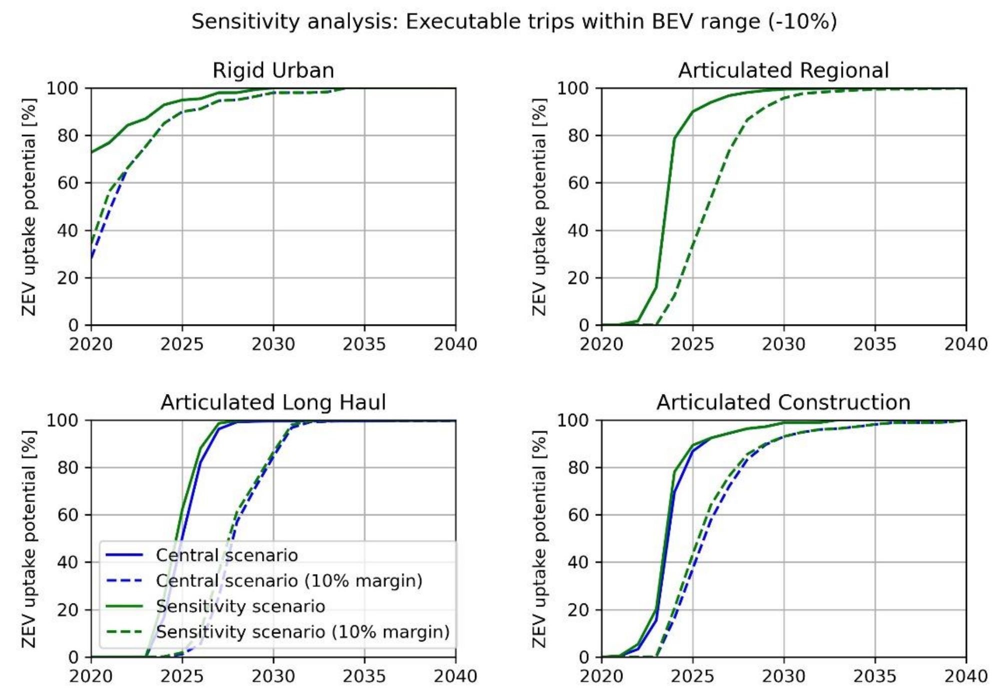

Figure 56: Impact of the ‘Executable trips within BEV range (-10%)’ scenario on the ZEV uptake potentials for the EU+UK.

In case it is demanded that 95% of trips can be covered with the BEVs dimensioned in this study, the uptake potential of the rigid urban delivery truck is reduced by approximately 20%. This effect is similar to that of the higher variation in daily distance.

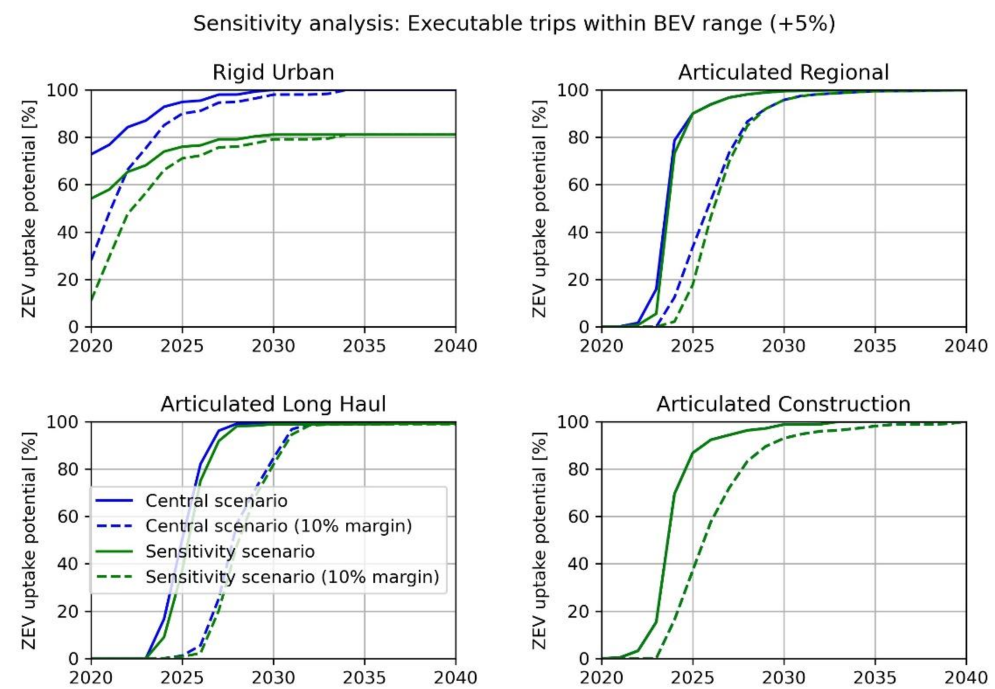

Figure 57: Impact of the ‘Executable trips within BEV range (+5%)’ scenario on ZEV uptake potentials for the EU+UK.

I.3.3 Average daily distance

From detailed deployment data available for the Netherlands only it can be seen that the value used in this study for the average daily distance might be an overestimation of approximately 25%. For other countries this could not been verified. The effect of reducing the average daily mileage by 25% is explored in this scenario. The annual distance is divided by 265 working days to arrive at the average daily distance.

As shown in the figure below for this scenario the potential uptake pace is slightly slower. As explained in section 6.3.1, this is the result of a much larger part of the fleet being indicated as a regional delivery truck instead of a long haul truck, since the split point of 400 km is kept the same (see section 6.2.2). Therefore the share of vehicles with a very low mileage (which cannot cost-effectively be electrified), also increases. As a result, the total zero-emission vehicle uptake potential slightly decreases. However, this is more a modelling artefact than an actual assessed impact because in reality there is not a clear split in regional delivery or long haul trucks since they are actually the same vehicle.

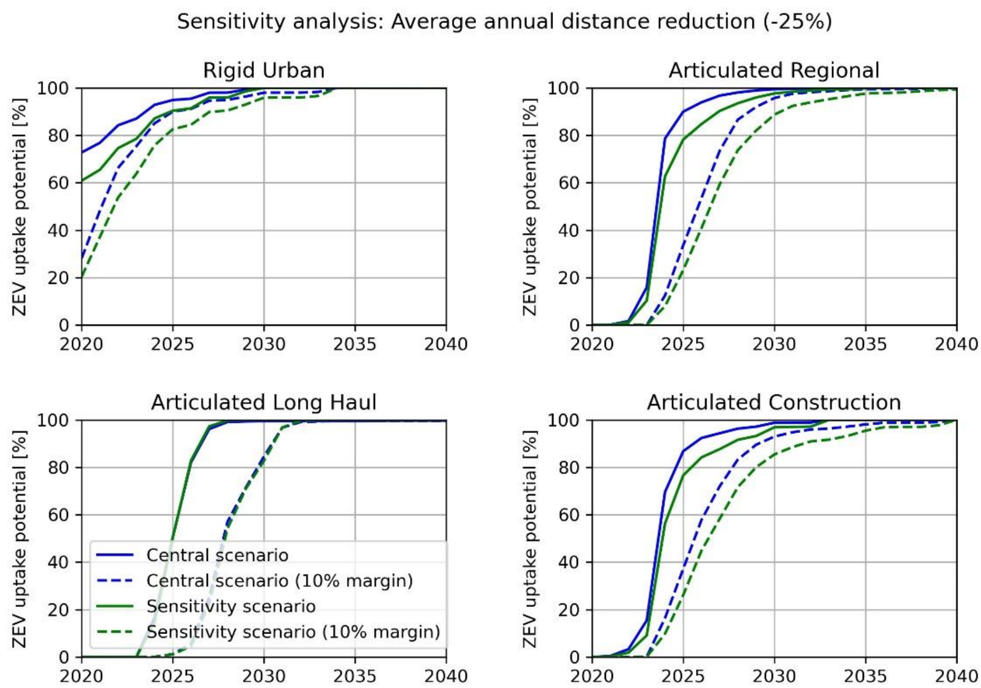

Figure 58: Impact of the '-25% reduction in yearly kilometres' scenario on ZEV uptake potentials for the EU+UK.

I.3.4 Summary for deployment-related parameter variations

In the table below the differences in ZEV uptake potentials for various deployment-related parameter variation scenarios are listed relative to the central scenario. A distinction is made between the BEVs and FCEVs such that the effect on both can be assessed separately.

Table 44: Summary of the impacts on BEV and FCEV uptake potentials per vehicle type for every deployment parameter variation scenario for the EU+UK.

Scenario	**Vehicle type**	**2030**		**2040**	
		BEV	**FCEV**	**BEV**	**FCEV**
Central scenario	Rigid Urban	100.0%		100.0%	
	Articulated Regional	99.4%		100.0%	
	Articulated Long Haul	99.5%	0.0%	99.6%	0.1%
	Articulated Construction	98.8%	0.0%	100.0%	0.0%
Executable trips within BEV range (+5%)	Rigid Urban	-18.9%		-18.9%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	-0.6%	0.0%	-0.7%	0.1%
	Articulated Construction	0.0%	0.0%	0.0%	0.0%
Executable trips within BEV range (-10%)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	0.4%	0.0%	0.3%	-0.1%
	Articulated Construction	0.0%	0.0%	0.0%	0.0%
Average annual distance reduction (-25%)	Rigid Urban	0.0%		0.0%	
	Articulated Regional	-1.8%		0.0%	
	Articulated Long Haul	0.5%	0.0%	0.4%	-0.1%
	Articulated Construction	-1.9%	0.0%	0.0%	0.0%
Higher daily distance variation (status quo)	Rigid Urban	-18.9%		-18.9%	
	Articulated Regional	0.0%		0.0%	
	Articulated Long Haul	-1.1%	0.0%	-1.3%	0.3%
	Articulated Construction	-9.5%	0.0%	-9.5%	4.6%

J Road tolling

In a number of countries within the EU+UK road tolls apply for trucks. The following tables show the country-specific road tolls, either distance-based and/or time-based for a medium truck (7.7-16 ton) and a tractor-trailer truck (>32 ton). A distinction is made between diesel trucks and zero-emission trucks. The data on road tolling is used for the policy-driven scenario described in section 7.2. A list of sources for the tolling information is included in Table 53.

Table 45: Distance-based road tolls per country (in €/km) for a medium diesel truck (7.5-16t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	0.203	0.203	0.203	0.203
Belgium	0.135	0.135	0.135	0.135
Bulgaria	0.105	0.105	0.105	0.105
Croatia	0.126	0.126	0.126	0.126
Cyprus	-	-	-	-
Czech Republic	0.075	0.075	0.075	0.075
Denmark	0.128	0.128	0.128	0.128
Estonia	-	-	-	-
Finland	-	-	-	-
France	0.263	0.263	0.263	0.263
Germany	0.126	0.126	0.126	0.126
Greece	0.154	0.154	0.154	0.154
Hungary	0.097	0.097	0.097	0.097
Ireland	0.150	0.150	0.150	0.150
Italy	0.128	0.128	0.128	0.128
Latvia	-	-	-	-
Lithuania	-	-	-	-
Luxembourg	-	-	-	-
Malta	-	-	-	-
Netherlands	0.126	0.126	0.126	0.126
Poland	0.055	0.055	0.055	0.055
Portugal	0.116	0.116	0.116	0.116
Romania	-	-	-	-
Slovakia	0.167	0.167	0.167	0.167
Slovenia	0.185	0.185	0.185	0.185
Spain	-	-	-	-
Sweden	-	-	-	-
United Kingdom	-	-	-	-

Table 46: Distance-based road tolls per country (in €/km) for a medium zero-emission truck (7.5-16t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	0.051	0.051	0.102	0.203
Belgium	0.135	0.034	0.067	0.135
Bulgaria	0.105	0.026	0.053	0.105
Croatia	0.126	0.126	0.126	0.126
Cyprus	-	-	-	-
Czech Republic	0.075	0.019	0.038	0.075
Denmark	0.128	0.032	0.064	0.128
Estonia	-	-	-	-
Finland	-	-	-	-
France	0.263	0.263	0.263	0.263
Germany	0.000	0.032	0.063	0.126
Greece	0.154	0.154	0.154	0.154
Hungary	0.097	0.024	0.049	0.097
Ireland	0.150	0.038	0.075	0.150
Italy	0.128	0.128	0.128	0.128
Latvia	-	-	-	-
Lithuania	-	-	-	-
Luxembourg	-	-	-	-
Malta	-	-	-	-
Netherlands	0.126	0.032	0.063	0.126
Poland	0.055	0.014	0.028	0.055
Portugal	0.116	0.116	0.116	0.116
Romania	-	-	-	-
Slovakia	0.167	0.042	0.084	0.167
Slovenia	0.185	0.046	0.093	0.185
Spain	-	-	-	-
Sweden	-	-	-	-
United Kingdom	-	-	-	-

Table 47: Distance-based road tolls per country (in €/km) for a diesel tractor-trailer (>32t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	0.423	0.423	0.423	0.423
Belgium	0.149	0.149	0.149	0.149
Bulgaria	0.105	0.105	0.105	0.105
Croatia	0.251	0.251	0.251	0.251
Cyprus	-	-	-	-
Czech Republic	0.202	0.202	0.202	0.202
Denmark	0.154	0.154	0.154	0.154
Estonia	-	-	-	-
Finland	-	-	-	-
France	0.347	0.347	0.347	0.347
Germany	0.183	0.183	0.183	0.183
Greece	0.215	0.215	0.215	0.215
Hungary	0.241	0.241	0.241	0.241
Ireland	0.191	0.191	0.191	0.191
Italy	0.152	0.152	0.152	0.152
Latvia	-	-	-	-
Lithuania	-	-	-	-
Luxembourg	-	-	-	-
Malta	-	-	-	-
Netherlands	0.130	0.130	0.130	0.130
Poland	0.055	0.055	0.055	0.055
Portugal	0.166	0.166	0.166	0.166
Romania	-	-	-	-
Slovakia	0.176	0.176	0.176	0.176
Slovenia	0.428	0.428	0.428	0.428
Spain	-	-	-	-
Sweden	-	-	-	-
United Kingdom	-	-	-	-

Table 48: Distance-based road tolls per country (in €/km) for a zero-emission tractor-trailer (>32t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	0.106	0.106	0.212	0.423
Belgium	0.149	0.037	0.074	0.149
Bulgaria	0.105	0.026	0.053	0.105
Croatia	0.251	0.251	0.251	0.251
Cyprus	-	-	-	-
Czech Republic	0.202	0.051	0.101	0.202
Denmark	0.154	0.038	0.077	0.154
Estonia	-	-	-	-
Finland	-	-	-	-
France	0.347	0.347	0.347	0.347
Germany	0.000	0.046	0.092	0.183
Greece	0.215	0.215	0.215	0.215
Hungary	0.241	0.060	0.121	0.241
Ireland	0.191	0.048	0.095	0.191
Italy	0.152	0.152	0.152	0.152
Latvia	-	-	-	-
Lithuania	-	-	-	-
Luxembourg	-	-	-	-
Malta	-	-	-	-
Netherlands	0.130	0.033	0.065	0.130
Poland	0.055	0.014	0.028	0.055
Portugal	0.166	0.166	0.166	0.166
Romania	-	-	-	-
Slovakia	0.176	0.044	0.088	0.176
Slovenia	0.428	0.107	0.214	0.428
Spain	-	-	-	-
Sweden	-	-	-	-
United Kingdom	-	-	-	-

Table 49: Time-based road tolls per country (in €/year) for a medium diesel truck (7.5-16t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	-	-	-	-
Belgium	-	-	-	-
Bulgaria	-	-	-	-
Croatia	-	-	-	-
Cyprus	-	-	-	-
Czech Republic	-	-	-	-
Denmark	-	-	-	-
Estonia	600	600	600	600
Finland	-	-	-	-
France	-	-	-	-
Germany	-	-	-	-
Greece	-	-	-	-
Hungary	-	-	-	-
Ireland	-	-	-	-
Italy	-	-	-	-
Latvia	427	427	427	427
Lithuania	753	753	753	753
Luxembourg	750	750	750	750
Malta	-	-	-	-
Netherlands	-	-	-	-
Poland	-	-	-	-
Portugal	-	-	-	-
Romania	560	560	560	560
Slovakia	-	-	-	-
Slovenia	-	-	-	-
Spain	-	-	-	-
Sweden	750	750	750	750
United Kingdom	762	762	762	762

Table 50: Time-based road tolls per country (in €/year) for a medium zero-emission truck (7.5-16t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	-	-	-	-
Belgium	-	-	-	-
Bulgaria	-	-	-	-
Croatia	-	-	-	-
Cyprus	-	-	-	-
Czech Republic	-	-	-	-
Denmark	-	-	-	-
Estonia	600	150	300	600
Finland	-	-	-	-
France	-	-	-	-
Germany	-	-	-	-
Greece	-	-	-	-
Hungary	-	-	-	-
Ireland	-	-	-	-
Italy	-	-	-	-
Latvia	427	107	214	427
Lithuania	753	188	377	753
Luxembourg	750	188	375	750
Malta	-	-	-	-
Netherlands	-	-	-	-
Poland	-	-	-	-
Portugal	-	-	-	-
Romania	560	140	280	560
Slovakia	-	-	-	-
Slovenia	-	-	-	-
Spain	-	-	-	-
Sweden	750	188	375	750
United Kingdom	762	762	762	762

Table 51: Time-based road tolls per country (in €/year) for a diesel tractor-trailer (>32t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	-	-	-	-
Belgium	-	-	-	-
Bulgaria	-	-	-	-
Croatia	-	-	-	-
Cyprus	-	-	-	-
Czech Republic	-	-	-	-
Denmark	-	-	-	-
Estonia	1,000	1,000	1,000	1,000
Finland	-	-	-	-
France	-	-	-	-
Germany	-	-	-	-
Greece	-	-	-	-
Hungary	-	-	-	-
Ireland	-	-	-	-
Italy	-	-	-	-
Latvia	711	711	711	711
Lithuania	753	753	753	753
Luxembourg	1,250	1,250	1,250	1,250
Malta	-	-	-	-
Netherlands	-	-	-	-
Poland	-	-	-	-
Portugal	-	-	-	-
Romania	1,210	1,210	1,210	1,210
Slovakia	-	-	-	-
Slovenia	-	-	-	-
Spain	-	-	-	-
Sweden	1,250	1,250	1,250	1,250
United Kingdom	1,172	1,172	1,172	1,172

Table 52: Time-based road tolls per country (in €/year) for a zero-emission tractor-trailer (>32t).

Country	2020-2023	2024-2029	2030-2034	2035-2040
Austria	-	-	-	-
Belgium	-	-	-	-
Bulgaria	-	-	-	-
Croatia	-	-	-	-
Cyprus	-	-	-	-
Czech Republic	-	-	-	-
Denmark	-	-	-	-
Estonia	1,000	250	500	1,000
Finland	-	-	-	-
France	-	-	-	-
Germany	-	-	-	-
Greece	-	-	-	-
Hungary	-	-	-	-
Ireland	-	-	-	-
Italy	-	-	-	-
Latvia	711	178	356	711
Lithuania	753	188	377	753
Luxembourg	1,250	313	625	1,250
Malta	-	-	-	-
Netherlands	-	-	-	-
Poland	-	-	-	-
Portugal	-	-	-	-
Romania	1,210	303	605	1,210
Slovakia	-	-	-	-
Slovenia	-	-	-	-
Spain	-	-	-	-
Sweden	1,250	313	625	1,250
United Kingdom	1,172	1,172	1,172	1,172

Table 53: Sources for tolling cost information per country.

Country	Source	Comment
Austria	ASFINAG (2022)	Includes 75% ZEV reduction from today
Belgium	Viapass (2022)	
Bulgaria	Toll Pass (2022)	
Croatia	European Commission (2019)	Exempt from CO2-based tolling due to concessions
Cyprus		No tolls
Czech Republic	Mytocz (2022)	
Denmark	Transportministeriet (2022)	Assuming distance-based adoption
Estonia	Transpordiamet (2022)	
Finland		No tolls
France	European Commission (2019)	Exempt from CO_2-based tolling due to concessions
Germany	Toll Collect (2022)	Includes 100% ZEV reduction from today
Greece	European Commission (2019)	Exempt from CO_2-based tolling due to concessions
Hungary	HU-GO (2022)	
Ireland		Exempt from CO_2-based tolling due to concessions, assuming state refunds reduction as currently foreseen
Italy	European Commission (2019)	Exempt from CO_2-based tolling due to concessions
Latvia	Lvvignette (2022)	
Lithuania	Lithuanian Road Administration (2022)	
Luxembourg	Eurovignette.eu (2022)	
Malta		No tolls
Netherlands	Eerste Kamer (2022)	Assuming introduction of distance-based tolling as adopted
Poland	E-toll (2022)	
Portugal	European Commission (2019)	Exempt from CO_2-based tolling due to concessions
Romania	European Commission (2019)	
Slovakia	Myto (2022)	
Slovenia	Dars (2022)	
Spain	-	Few remaining concession sections which will be exempt from CO_2-based tolling
Sweden	Eurovignette.eu (2022)	
United Kingdom	Department for Transport (2019)	Ignoring temporary suspension until July 2023

K Effects of temperature on energy consumption

This appendix shows the data used to determine the influence of the ambient temperature on the energy consumption. The method to account for temperature influence on energy consumption is described in section 3.3.

Table 54 Assumed 'representative' monthly temperatures per country based on (World Meteorological Organization , 2022). Red is high temperature, blue is low temperature.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Austria	0	1	5	9	14	17	19	19	15	9	4	1
Belgium	2	3	5	8	12	14	17	16	13	10	6	3
Bulgaria	-3	0	3	8	13	16	18	18	14	9	4	0
Croatia	-2	0	4	9	13	17	18	18	14	9	4	0
Cyprus	9	9	12	15	20	25	28	28	24	20	15	11
Czechia	-1	0	4	8	13	16	18	18	14	9	4	0
Denmark	-1	-1	1	5	10	14	15	15	12	9	4	1
Estonia	-5	-6	-2	3	8	13	15	14	10	5	0	-3
Finland	-7	-7	-3	2	8	13	15	14	9	4	-1	-5
France	4	5	7	9	13	16	18	18	15	11	7	5
Germany	0	0	4	7	11	14	16	16	13	8	4	1
Greece	8	8	10	13	18	23	25	25	21	17	13	9
Hungary	-1	1	5	10	15	18	20	20	15	10	4	0
Ireland	4	4	6	7	10	12	14	14	12	9	6	5
Italy	6	7	9	11	15	19	22	22	19	15	10	7
Latvia	-6	-6	-2	4	9	13	15	15	11	6	1	-3
Lithuania	-5	-5	-1	6	11	14	17	16	11	6	1	-4
Luxembourg	0	1	4	7	12	14	17	16	13	9	4	1
Malta	11	11	12	14	18	21	24	25	23	19	16	13
Netherlands	2	2	5	7	11	13	15	15	13	9	6	3
Poland	-3	-2	2	7	12	15	17	17	12	7	2	-2
Portugal	8	9	10	11	14	17	18	18	17	15	11	9
Romania	-2	-1	4	9	14	18	20	20	15	10	4	-1
Slovakia	-1	1	5	10	14	18	20	20	15	10	5	0
Slovenia	-1	1	5	8	13	16	19	18	15	10	4	0
Spain	5	6	10	11	15	20	23	23	19	14	9	6
Sweden	-4	-4	-1	4	9	14	16	15	11	7	2	-2
United Kingdom	5	5	7	9	12	15	17	17	14	11	8	5

Table 55: Determined additional energy consumption per country for Urban rigid and Articulated regional delivery BEVs.

	Urban rigid (medium battery)			Urban rigid (large battery)			Articulated regional delivery (medium			Articulated regional delivery (large battery)		
	2020	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**
Austria	1.3%	1.1%	1.1%	1.4%	1.2%	1.2%	2.3%	1.9%	1.9%	2.7%	2.3%	2.3%
Belgium	0.7%	0.7%	0.7%	0.8%	0.8%	0.8%	1.4%	1.3%	1.3%	1.8%	1.5%	1.5%
Bulgaria	1.7%	1.7%	1.7%	1.9%	1.8%	1.8%	3.0%	2.7%	2.7%	3.6%	3.2%	3.2%
Croatia	1.5%	1.5%	1.5%	1.6%	1.6%	1.6%	2.7%	2.4%	2.4%	3.3%	2.9%	2.8%
Cyprus	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	1.2%	0.6%	0.6%
Czechia	1.3%	1.3%	1.3%	1.4%	1.4%	1.4%	2.4%	2.1%	2.1%	2.9%	2.5%	2.5%
Denmark	1.3%	1.3%	1.3%	1.4%	1.4%	1.4%	2.4%	2.1%	2.1%	2.9%	2.5%	2.5%
Estonia	2.5%	2.4%	2.4%	2.6%	2.5%	2.5%	4.3%	3.8%	3.8%	5.1%	4.5%	4.5%
Finland	2.9%	2.8%	2.7%	3.1%	3.0%	3.0%	5.0%	4.4%	4.4%	6.0%	5.2%	5.2%
France	0.5%	0.4%	0.4%	0.5%	0.5%	0.5%	1.0%	0.9%	0.9%	1.3%	1.1%	1.1%
Germany	1.2%	1.2%	1.1%	1.3%	1.2%	1.2%	2.2%	1.9%	1.9%	2.6%	2.3%	2.3%
Greece	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.1%	0.5%	0.3%	0.3%
Hungary	1.4%	1.4%	1.4%	1.5%	1.5%	1.5%	2.5%	2.2%	2.2%	3.0%	2.7%	2.6%
Ireland	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.9%	0.8%	0.8%	1.2%	1.0%	1.0%
Italy	0.1%	0.1%	0.1%	0.2%	0.1%	0.1%	0.5%	0.4%	0.4%	0.7%	0.6%	0.6%
Latvia	2.6%	2.5%	2.4%	2.7%	2.6%	2.6%	4.4%	3.9%	3.9%	5.3%	4.7%	4.6%
Lithuania	2.3%	2.2%	2.2%	2.4%	2.3%	2.3%	3.9%	3.5%	3.5%	4.7%	4.1%	4.1%
Luxembourg	1.2%	1.1%	1.1%	1.3%	1.2%	1.2%	2.2%	1.9%	1.9%	2.6%	2.3%	2.3%
Malta	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.1%	0.1%
Netherlands	0.8%	0.7%	0.7%	0.8%	0.8%	0.8%	1.5%	1.3%	1.3%	1.8%	1.6%	1.6%
Poland	1.8%	1.7%	1.7%	1.9%	1.8%	1.8%	3.1%	2.8%	2.8%	3.7%	3.3%	3.2%
Portugal	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.1%	0.3%	0.2%	0.2%
Romania	1.7%	1.6%	1.6%	1.8%	1.7%	1.7%	2.9%	2.6%	2.6%	3.5%	3.1%	3.1%
Slovakia	1.4%	1.3%	1.3%	1.5%	1.4%	1.4%	2.4%	2.2%	2.2%	2.9%	2.6%	2.5%
Slovenia	1.4%	1.3%	1.3%	1.5%	1.4%	1.4%	2.4%	2.1%	2.1%	2.9%	2.5%	2.5%
Spain	0.3%	0.2%	0.2%	0.3%	0.3%	0.3%	0.8%	0.6%	0.6%	1.0%	0.8%	0.8%
Sweden	2.0%	1.9%	1.9%	2.1%	2.1%	2.1%	3.5%	3.1%	3.1%	4.2%	3.7%	3.6%
United Kingdom	0.3%	0.3%	0.3%	0.4%	0.4%	0.4%	0.8%	0.7%	0.7%	1.1%	0.9%	0.9%

Table 56: Determined additional energy consumption per country for Articulated long haul and Articulated construction BEVs

	Articulated long haul (medium battery)			Articulated long haul (large battery)			Articulated construction (medium battery)			Articulated construction (large battery)		
	2020	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**
Austria	3.4%	2.8%	2.4%	5.0%	3.9%	3.8%	1.8%	1.6%	1.6%	2.6%	2.2%	2.2%
Belgium	2.3%	1.9%	1.7%	3.4%	2.7%	2.7%	1.1%	1.0%	1.0%	1.7%	1.5%	1.5%
Bulgaria	4.5%	3.9%	3.4%	6.6%	5.4%	5.3%	2.4%	2.3%	2.3%	3.4%	3.2%	3.1%
Croatia	4.1%	3.5%	3.1%	5.9%	4.8%	4.7%	2.1%	2.0%	2.0%	3.1%	2.8%	2.8%
Cyprus	2.3%	1.5%	0.9%	4.7%	3.2%	3.1%	0.0%	0.0%	0.0%	0.9%	0.6%	0.5%
Czechia	3.6%	3.1%	2.7%	5.2%	4.3%	4.2%	1.9%	1.8%	1.8%	2.7%	2.5%	2.4%
Denmark	3.6%	3.1%	2.7%	5.2%	4.2%	4.2%	1.9%	1.8%	1.8%	2.7%	2.5%	2.4%
Estonia	6.4%	5.5%	4.8%	9.2%	7.5%	7.4%	3.4%	3.2%	3.2%	4.8%	4.4%	4.3%
Finland	7.4%	6.4%	5.6%	11%	8.7%	8.6%	3.9%	3.7%	3.7%	5.6%	5.2%	5.1%
France	1.7%	1.4%	1.2%	2.5%	2.0%	2.0%	0.7%	0.7%	0.7%	1.2%	1.1%	1.0%
Germany	3.3%	2.8%	2.5%	4.8%	3.9%	3.8%	1.7%	1.6%	1.6%	2.5%	2.3%	2.2%
Greece	1.3%	0.8%	0.3%	3.2%	2.1%	2.0%	0.1%	0.0%	0.0%	0.3%	0.3%	0.2%
Hungary	3.8%	3.3%	2.9%	5.5%	4.5%	4.4%	2.0%	1.9%	1.9%	2.9%	2.6%	2.6%
Ireland	1.5%	1.3%	1.1%	2.4%	1.9%	1.8%	0.7%	0.6%	0.6%	1.1%	1.0%	1.0%
Italy	1.0%	0.8%	0.7%	1.9%	1.3%	1.3%	0.3%	0.3%	0.3%	0.7%	0.6%	0.6%
Latvia	6.6%	5.7%	5.0%	9.5%	7.8%	7.6%	3.5%	3.3%	3.3%	5.0%	4.6%	4.5%
Lithuania	5.9%	5.0%	4.4%	8.4%	6.9%	6.8%	3.1%	3.0%	3.0%	4.4%	4.1%	4.0%
Luxembourg	3.3%	2.8%	2.4%	4.8%	3.9%	3.8%	1.7%	1.6%	1.6%	2.5%	2.3%	2.2%
Malta	1.3%	0.7%	0.3%	3.0%	2.0%	1.9%	0.0%	0.0%	0.0%	0.3%	0.1%	0.0%
Netherlands	2.3%	2.0%	1.7%	3.5%	2.8%	2.7%	1.1%	1.1%	1.1%	1.7%	1.6%	1.5%
Poland	4.6%	4.0%	3.5%	6.7%	5.5%	5.4%	2.5%	2.3%	2.3%	3.5%	3.2%	3.2%
Portugal	0.6%	0.4%	0.3%	1.1%	0.8%	0.7%	0.0%	0.0%	0.0%	0.3%	0.2%	0.2%
Romania	4.4%	3.8%	3.3%	6.4%	5.2%	5.1%	2.3%	2.2%	2.2%	3.3%	3.1%	3.0%
Slovakia	3.7%	3.1%	2.7%	5.3%	4.3%	4.3%	1.9%	1.8%	1.8%	2.8%	2.5%	2.5%
Slovenia	3.6%	3.1%	2.7%	5.3%	4.3%	4.2%	1.9%	1.8%	1.8%	2.7%	2.5%	2.5%
Spain	1.3%	1.1%	0.9%	2.3%	1.6%	1.6%	0.5%	0.5%	0.5%	0.9%	0.8%	0.8%
Sweden	5.2%	4.4%	3.9%	7.5%	6.1%	6.0%	2.8%	2.6%	2.6%	3.9%	3.6%	3.5%
United Kingdom	1.4%	1.2%	1.0%	2.2%	1.7%	1.7%	0.6%	0.6%	0.5%	1.0%	0.9%	0.9%