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TOTAL COST OF OWNERSHIP FOR TRACTOR-TRAILERS IN EUROPE: BATTERY ELECTRIC VERSUS DIESEL

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EXECUTIVE SUMMARY

The decarbonization of road freight will require the transition away from internal combustion engines and toward zero-emission powertrains powered by renewable energy. Such transition rests on several pillars: sufficient supply of zero-emission vehicles by truck manufacturers, adequate infrastructure roll-out, a robust demand for these technologies, and targeted policy measures to accelerate the technology deployment. The last two points are the subject of this report.

This study analyzes the total cost of ownership (TCO) of the application of battery-electric trucks (BET) to the highest emitting road freight segment: long-distance tractor-trailers. The analysis covers seven European countries, Germany, France, Spain, Italy, Poland, the Netherlands, and the United Kingdom, which accounted for more than 75% of truck sales in the European Union in 2019.

Through a detailed analysis of vehicle costs, financing and residual value, registration and ownership taxes, electricity and diesel costs, maintenance costs, road tolls, battery replacement, and charging infrastructure costs, the study evaluates the TCO difference between BETs and diesel trucks between 2020 and 2030. The evaluation is done from a first-user perspective over a 5-year analysis period. Our analysis finds that:

» From a first-user perspective, BETs can achieve TCO parity with diesel tractor-trailers during this decade for all the considered countries, without any additional policy support. Still, there are substantial differences across countries mainly driven by the disparities in electricity and diesel prices, road tolls, and the currently implemented policy measures. BETs operating in Germany, France, and the Netherlands can reach immediate TCO parity with diesel tractor-trailers in 2021–2022, whereas other countries witness delays in parity time until the middle of the decade. The years in which TCO parity is achieved in each country are shown in Figure ES 1.

Figure ES 1. Year when TCO parity between battery-electric and diesel tractor-trailers is achieved, during the first 5-year ownership period, under currently adopted policies in the countries considered.

» Regulatory support can all but eliminate the TCO gap between BETs and diesel tractor-trailers already today. The policy measures analyzed include purchase premiums, road tolls exemptions, and carbon pricing. While some of these policies have already been adopted in the countries analyzed, others—such as the Eurovignette Directive, or the inclusion of transport into the European Emissions Trading System—are active policy developments that have not yet been adopted. The impact of these policies on the countries analyzed is shown in Figure ES 2.

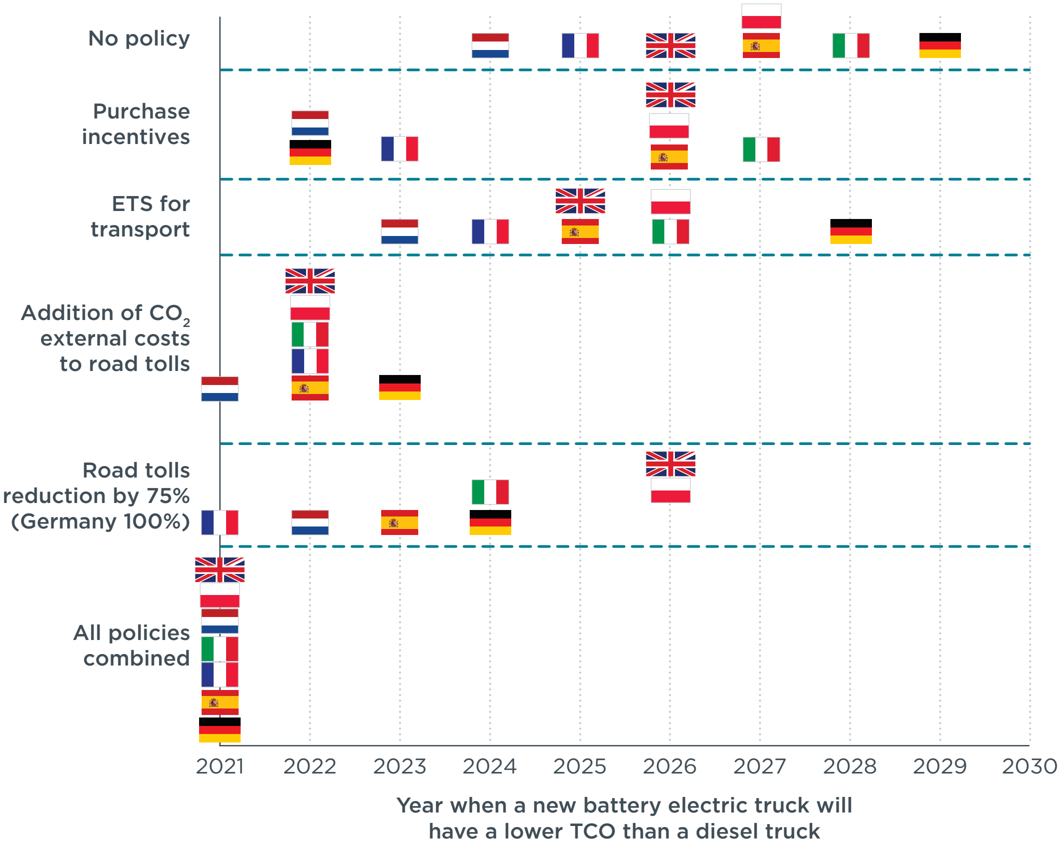

Figure ES 2. Impact of policy measures on bringing forward the year of TCO parity between battery-electric and diesel tractor-trailers during the first 5-year ownership period.

Based on our findings, we recommend the following policy interventions to accelerate the deployment of BETs in the EU:

» **Implement the Eurovignette Directive into national law as expeditiously as possible.** Partial exemption of BET distance-based road tolls by 75% can help BETs reach TCO parity with their diesel counterparts between 2021 and 2023. Furthermore, the CO_2 external cost charge in the road toll, of up to 16 EUR cents/km, further contributes to closing the TCO gap, achieving TCO parity in the first half of the current decade.

» **Purchase premiums for trucks should be limited to incentivize the purchase of zero-emission trucks in the near term and exclude all combustion powered trucks.** Purchase incentives is a powerful policy tool to help close the price and TCO gap between diesel trucks and BETs. For example, an incentive of €50,000 per truck can help BETs achieve earlier TCO parity in 1–2 years. Given that subsidies are not fiscally sustainable in the long term, they must be limited in duration and scope. A malus component in such subsidy schemes, applicable to combustion powered trucks, can help manage the fiscal sustainability of these incentive programs.

» **Extend the European Emissions Trading Systems (ETS) to include transport as proposed in the Fit for 55 package.** Currently, only Germany imposes carbon pricing for transport increasing from €25 per tonne of CO_2 equivalent in 2021 to €55/tonne CO_{2e} by 2025. This results in a 1-year reduction in TCO parity time between BETs and diesel trucks. Imposing higher carbon pricing and implementing this policy across all member states narrow down the TCO gap between BETs and their diesel counterparts.

» **Implement fiscal incentives for use of renewable electricity used for BET charging.** Partially waiving the nonrecoverable electricity taxes has a substantial impact on the time to achieve TCO parity of BETs with diesel trucks. For example, a 50% reduction on those taxes would reduce BET parity time with diesel by 3 years. The revision of the Energy Taxation Directive should support the business case for zero-emission trucks by allowing member states to apply tax discounts for the renewable electricity used for charging trucks.

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INTRODUCTION

The transportation sector is responsible for almost 30% of greenhouse gas (GHG) emissions in Europe, and unlike other sectors, emissions did not gradually decline in this sector compared to the 1990 reference year. The GHG emissions of the transport sector in Europe exceeded 1 billion tonnes of CO_2 equivalent in 2018, with road transport's contribution around 70%. Cars and light-duty vehicles are responsible for close to 52%, while the heavy-duty vehicles segment claims 19% (European Environment Agency, 2020).

In the past two decades, most of the regulatory efforts to curb the climate impact of road transport have mainly targeted passenger and light-duty vehicles. Nonetheless, in the past few years, heavy-duty vehicles (HDVs) have become the subject of regulatory interventions aimed at improving their fuel consumption, which has remained relatively stagnant over the past decades in comparison to passenger vehicles (Delgado & Rodríguez, 2018). The most prominent example of such regulatory measures is the introduction of CO_2 standards for HDVs, which mandate a fleet-wide reduction in CO_2 emissions of 15% in 2025 and 30% in 2030 for new trucks, relative to the emissions performance in the period between July 1, 2019, to June 30, 2020 (Parliament and Council of the European Union, 2019).

Still, a recent ICCT analysis (Buysse et al., 2021) finds that the HDV CO_2 standards in their current form fall short of what is needed to achieve the goals set out in the European Green Deal (European Commission, 2019). The latter aims at creating a legally binding target to achieve climate carbon neutrality by 2050, including a subtarget to reduce transport-related GHG emissions by 90% in the same time frame relative to 1990 levels. To get there, as clearly articulated in the European Sustainable and Smart Mobility Strategy (European Commission, 2020b), it is necessary to rapidly increase the uptake of zero-emission vehicles across all transportation modes. As part of the strategy, the European Commission target is to have 80,000 zero-emission trucks in operation by 2030, a target that is not sufficient to meet the decarbonization goals of the European Union and that falls short of the industry's own targets: the European Automobile Manufacturers Association (ACEA) estimates that at least 200,000 zero-emission trucks should be in operation by 2030 (ACEA, 2021).

Several electrification pathways are currently being explored, including battery-electric trucks (BETs) and hydrogen fuel cell electric trucks (FCETs), as well as trucks powered by electric road systems. Battery-electric passenger vehicles have progressed significantly, mainly thanks to advances in battery technology. Such advances have also enabled the application of electric drive across other segments that are more challenging to decarbonize, such as long-distance tractor-trailers. However, many uncertainties still exist around the total cost of operation of such vehicles, impacting their large-scale deployment.

The goal of this study is to compare the total cost of ownership (TCO) of battery-electric tractor-trailers and their diesel counterparts. The analysis aims to identify main challenges facing BETs in achieving TCO parity with diesel trucks and provide policy recommendations that would bring their TCO-parity time forward.

This study analyzes tractor-trailers covering a daily distance of at least 500 km. Although cross-border travel is common in the EU, the calculation only considers trucks operating withing the boundaries of the country analyzed. The geographical scope of this study is limited to seven countries accounting for more than 75% of the HDV market (ICCT, 2019) in Europe: France, Germany, Italy, the Netherlands, Poland, Spain, and the United Kingdom. The TCO analysis is done from a commercial first-user perspective.

In addition, several policy interventions are analyzed and their impact on the TCO gap between BETs and diesel trucks is highlighted. Such policies can help catalyze the deployment of BETs in countries where the TCO gap between BETs and diesel trucks is high.

LITERATURE REVIEW

The TCO of alternative vehicle technologies has been the subject of extensive research and investigation over the past decade. Medium- and heavy-duty vehicle alternative technologies have gained momentum recently, driven by the imposed emissions standards and regulations worldwide on those vehicle segments. Several studies have assessed the TCO of different truck classes and for different applications, mainly in the European Union and the United States, focusing on two or more vehicle technologies and comparing alternative truck technologies to diesel trucks based on their economic performance. Those studies differ greatly in their inputs - which include vehicle energy efficiency, truck residual values, lifespan, daily driving range, and annual mileage of vehicles, and length of the analysis period, in addition to case-specific inputs, such as energy costs, discount rates, maintenance, and road tolls - as all these inputs vary from one country or city to the next. Therefore, their estimates are case oriented and cannot be generalized. Table 1 presents a summary of selected studies in the literature on the TCO of zero-emission trucks, highlighting main findings and insights.

Table 1. Summary of selected studies in the literature on the TCO of zero-emission trucks

Institution/Study	Application	TCO Components	Energy Efficiency	Main Findings
Institute of Transportation Studies, UC Davis, USA (Burke, 2020)	• Diesel, electric, and hydrogen HDV trucks • 100,000 to 134,000 mi/year and 150 to 300 mi daily driving range • 5-year analysis period	• Truck purchase • Energy • Maintenance • Residual value	• Electric: 240 kWh/100 mi (~1,5 kWh/km) in 2030 • Diesel: 8.7 mpg (~27 l/100 km) in 2030	• Battery cost should drop below $100/kWh to become cost competitive with diesel • BETs are more cost competitive in comparison to FCETs • FCETs can be more cost competitive than BETs for very high mileages (~600 mi)
ING Economics Department, the Netherlands (ING Economic Bureau, 2019)	• Diesel and electric 35–40 tonnes trucks • 60,000 to 100,000 km/year and 100 to 150 km daily driving range • 8-year analysis period	• Truck purchase • Energy and maintenance • Infrastructure • Insurance and financing	• Electric: 1.5 kWh/km in 2019 • Diesel: 25 l/100 km in 2019	• BETs can achieve TCO parity by the middle of the decade for an annual mileage of at least 100,000 km
Transport and Environment, Germany (Unterlohner, 2021)	• Diesel, electric, hydrogen, and e-diesel long-haulers • 136,750 km/year and 800 km daily driving range • 5-year analysis period	• Truck purchase • Energy • Infrastructure • Road charges • Taxes and levies	• Electric: 1.52 kWh/km in 2020 and 1.15 kWh/km in 2030 • Diesel: 29.86 l/100km in 2020 and 23.47 l/100 km in 2030	• BETs have a superior economic performance over all other alternative technologies. • BETs powered by renewable electricity can reach TCO parity by 2025
Lawrence Berkeley National Laboratory, USA (Phadke et al., 2021)	• Diesel and electric 36 tonnes long-haulers • 78,000 to 104,000 mi/year and 375 to 500 mi daily driving range • 3- to 15-year analysis period	• Truck purchase • Energy • Infrastructure • Maintenance • General operation	• Electric: 2.1 kWh/mi (~1,32 kWh/km) in 2020 for a 36 tonnes truck • Diesel: 5.9 mpg (~40 l/100 km) in 2020	• BETs present a 13% reduction compared to TCO and a 3-year pay-back period • Negligible payload penalty that can be overcome by light-weighting
International Council on Clean Transportation, USA (Hall & Lutsey, 2019)	• Diesel, electric, and hydrogen long-haulers • 140,000 mi/year and 190 mi daily driving range • 10-year analysis period	• Truck purchase • Energy and maintenance • Infrastructure	• Electric: 1.9 kWh/mi (~1,2 kWh/km) in 2019 without trailer	• BETs become less expensive by 2026 and FCETs by 2028 • BETs continue to have a better economic performance in comparison to FCETs up to 2030
Carnegie Mellon University, USA (Sripad & Viswanathan, 2019)	• Diesel and electric class 8 trucks • 80,000 to 100,000 mi/year and 500 miles/day driving range • 10-year analysis period	• Truck purchase • Energy and maintenance	• Electric: 2.3 kWh/mi (~1,44 kWh/km) in 2019 • Diesel: 8.5 mpg (~28 l/100 km) in 2019	• A 5-year payback period of a BET can be achieved through reduced vehicle drag, battery pack price below $150/kWh, electricity price below $0.2/kWh and battery pack replacement fraction below 50%
California Air Resources Board, USA (CARB, 2019)	• Diesel, electric, and hydrogen regional trucks • 54,000 mi/year and 180 miles/day driving range • 12-year analysis period	• Truck purchase • Energy and maintenance • Infrastructure • General operation	• Electric: 2.1 kWh/mi (~1,3 kWh/km) in 2018 for regional day cab tractor • Diesel: 5.9 mpg (~40 l/100 km) in 2018	• BETs can reach TCO parity by 2024 • FCET cost-parity is not possible before 2030
Atlas Public Policy, USA (Satterfield & Nigro, 2020)	• Diesel and electric long haulers • Up to 170,000 miles/year • 3- to 5-year analysis period	• Truck purchase • Energy and maintenance • Infrastructure • Taxes and levies	Not reported	• Depot charging for long-haul trucks is the most promising configuration for cost competitiveness of BETs
Aachen University, Germany (Mareev et al., 2018)	• Diesel and electric long haulers • 689 to 723 km/ day driving range • 3- to 12-year analysis period	• Truck purchase • Energy and maintenance • Infrastructure • Road charges	• Electric: 1.33–1.83 kWh/km	• BETs can become cost-effective with diesel trucks especially for long analysis periods • BETs would suffer a payload penalty of 20%
Institute of Automotive Technology, Technical University of Munich, Germany (Wolff et al., 2020)	• Diesel, hybrid, and electric long haulers. • 400–600 km/day driving range • 6-year analysis period	• Truck purchase • Energy • Infrastructure • CO_2 cost	Not reported	• Very high TCO for BETs due to a 22% payload penalty • FCETs are neither cost competitive nor emissions competitive due to high hydrogen prices and upfront emissions • Diesel hybrid is the best compromise for the costs-emissions tradeoffs

Burke (2020) conducted a TCO assessment for a variety of medium and HDV truck classes in the United States—focusing on diesel, electric, and fuel cell electric trucks—and concluded that BETs cannot be cost competitive with diesel trucks until the battery pack price drops below $100/kWh for long haulers. Lawrence Berkeley National Laboratory (Phadke et al., 2021) analyzed the technoeconomic performance of long haulers with very high mileage, reaching 500 miles a day (800 km) and 104,000 miles annually (167,000 km), and concluded that BETs would cost 12% less in comparison to diesel trucks, with a pay-back period of 3 years and negligible payload penalty. California Air Resources Board estimates that BET cost parity with diesel trucks will be achieved by 2024 for a daily driving range of 180 miles (288 km), while FCET cannot achieve TCO parity before 2030 (CARB, 2019). Other studies investigated several charging methods for BETs and concluded that depot charging at night is the most cost-effective charging configuration for long haulers, helping them achieving TCO parity later this decade (Satterfield & Nigro, 2020).

Other studies are EU specific, focusing mainly on long haulers in Germany, France, the United Kingdom, and the Netherlands. A series of studies conducted by Transport and Environment for several European countries estimate that BETs powered by renewable electricity will reach TCO parity with diesel trucks by the middle of the decade in France (Unterlohner, 2020a), the United Kingdom (Unterlohner, 2020b), and Germany (Unterlohner, 2021). In the Netherlands, BETs are expected to achieve cost parity by 2027 under the condition that the truck driven annual distance is no less than 100,000 km (ING Economic Bureau, 2019). Other studies focus on long-haulers in Germany with quiet different conclusions. Mareev et al. (2018) concludes that BETs can become cost-effective but not from a first-user perspective (analysis period above 5 years) while Wolff et al. (2020) clearly states that BETs will suffer a significant payload penalty exceeding 20%, and this will impact their TCO parity with diesel trucks significantly.

In this study, we present a detailed TCO analysis to comprehensively address the economic performance of battery-electric long-haul trucks in several EU countries. The countries of interest are Germany, France, the United Kingdom, the Netherlands, Italy, Spain, and Poland. Country-specific data are collected highlighting their differences and impact on TCO parity year for BETs used for long-haul trucking.

This study is the first to tackle the deployment of BETs across several EU member states using a comprehensive TCO assessment while clearly highlighting the different challenges facing BET technologies in each country. The study also suggests and quantifies policy interventions to bring the TCO parity forward.

METHODOLOGY AND DATA SOURCES

This study compares the TCO of battery-electric long-haul trucks versus their diesel counterparts. The TCO model focuses on the fixed and variable costs that are bound to differ between diesel and battery-electric trucks. These include vehicle upfront cost, financing and depreciation, fuel and energy expenditures, vehicle maintenance, battery replacement, road tolls, registration and ownership taxes, and charging infrastructure costs.

The TCO comparison is done for diesel and battery-electric tractor-trailers purchased between 2020 and 2030, over their first-buyer use (5 years). A main output of this analysis is the TCO difference between diesel and battery-electric tractor-trailers, calculated as the net present value (NPV) of all expenditures.

The TCO analysis is framed from the perspective of the first owner of the truck. The first-owner TCO analysis is done over a period of 5 years after registration, includes all nonrecoverable taxes applicable to the commercial use of the vehicles—for example, value added tax (VAT) is not included as it is a recoverable tax—and uses a discount rate of 9.5% (Krause & Donati, 2018) for calculating the NPV of cash flows during the analysis period. These parameters are summarized in Table 2 and are consistent with those used by the European Commission in its impact assessment of the CO_2 standards for trucks (European Commission, 2018).

Table 2. Summary of TCO model parameters for the considered perspective

Parameter	First-ownership perspective
Analysis period	5 years
Residual value	Considered
Discount rate	9.5%
Taxes	Only nonrecoverable taxes considered
VAT	Excluded
Road tolls	Included
CO_2 external cost	Excluded

USE CASE AND VEHICLE TECHNICAL SPECIFICATIONS

Tractor-trailers can be used in a variety of applications ranging from urban delivery to long-haul transportation. The latter use case represents the biggest challenge for electrification because of the daily distances the vehicles need to cover. Data available from fleet management systems, such as the data set shown in Figure 1, indicate that 70% of trucks drive a daily distance of less than 500 km per day. This figure increases to 95% when considering trips shorter than 660 km; therefore, the long-haul application analyzed in this study aims to cover those 95% of cases. However, given that we identify overnight charging as a key lever to reduce cost, the use case is a typical return-home route that is planned and is less representative of cross-border long-haul trips driven by the spot freight market.[1]

1 In the spot market, fleets are hired by a broker or third-party logistics, who in turn is paid by the shipper or receiver to arrange transportation. As such, the trip length, routes, and destinations cannot be planned from the perspective of the vehicle operator.

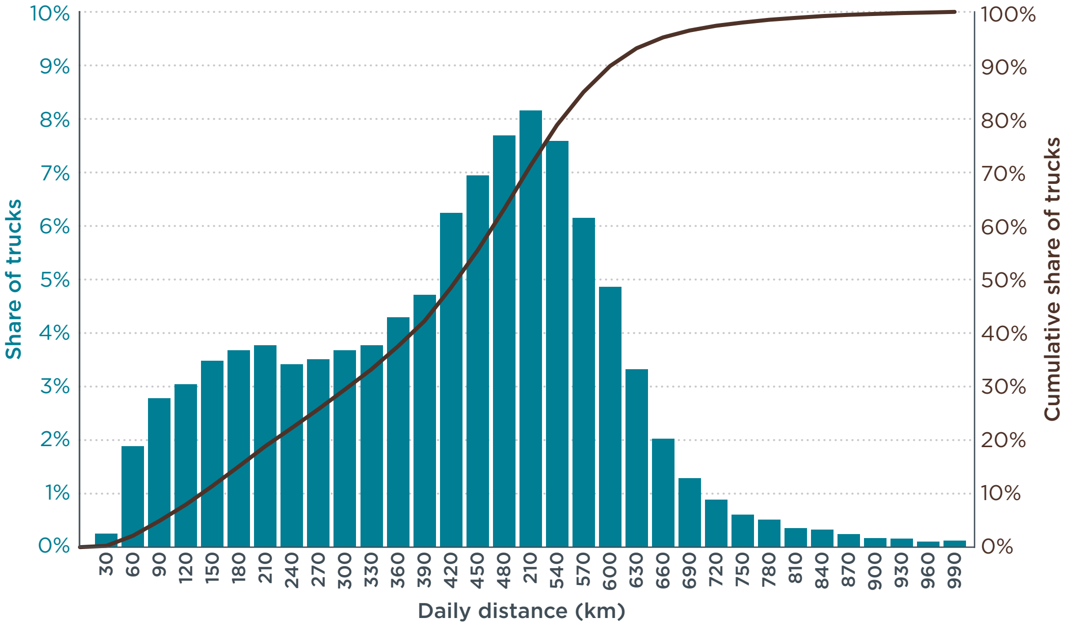

Figure 1. Average truck daily distance from a representative fleet, adapted from Wentzel (2020). (Germany-specific road freight activity reported in Unterlohner [2021] is in-line with the data used in this study.)

The technical specifications of the tractor-trailers analyzed are summarized in Table 3. The diesel vehicle was specified to match the technical characteristics of typical tractor-trailers currently in operation. The battery-electric vehicle was defined to match the performance of the diesel tractor-trailer, with its battery sized for a range of 500 km; that is, covering 70% of applications without the need for recharging and 95% of cases with a 45-minute charging event during the day, as will be discussed later in this section. The 500-km driving range considered in this study is assumed to be a fixed target for all truck models between 2020 and 2030.

Table 3. Technical specifications of the battery-electric and diesel tractor-trailers analyzed

	Diesel tractor-trailer	Battery-electric tractor-trailer
Gross vehicle weight	40 tonnes	42 tonnes[a]
Maximum payload	25.4–27.3 tonnes[b]	22.5–27.3 tonnes[b]
Axle configuration	4×2	4×2
Powertrain rated power	350 kW	350 kW
Transmission	12 speed	2 speed
Range single charge	—	~500 km[c]

[a] The HDV CO_2 standards include a derogation to allow 2 extra tonnes for zero-emission trucks.
[b] The trucks' curb weight changes in the analysis period due to chassis lightweight and battery energy density improvement; therefore, a range is given.
[c] As the vehicle efficiency improves in time, the battery size is reduced to maintain the target range.

The trucks' electric energy and diesel fuel consumption were estimated through model development and simulations.[2] The virtual models simulate the performance of the battery-electric and diesel tractor-trailers, using detailed component data to represent the behavior of the individual subsystems (e.g., battery, motor, energy management system, and battery and cabin thermal management systems) and a network of

2 The official vehicle simulation model used to certify the CO_2 emissions of trucks, called VECTO, is currently only limited to combustion-powered trucks. In this study, we use a commercial simulation tool called Simcenter Amesim to simulate the performance of the battery-electric tractor-trailers. Since the intended purpose of this study is to analyze the performance of battery-electric trucks under VECTO-like conditions, Simcenter Amesim was validated against VECTO using a representative diesel tractor-trailer.

feedback loops to simulate their interactions with each other and with the environment. The vehicle performance was evaluated over the same boundary conditions used in the official methodology to certify the CO_2 emissions of diesel trucks, EU Regulation 2017/2400 (Rodríguez, 2017). The electric energy and diesel fuel consumption of the vehicles were simulated over the long-haul cycle used for certification at two different payloads: a low payload of 2.6 tonnes and a reference payload of 19.3 tonnes as defined by the vehicle energy consumption calculation tool (VECTO) for long-haul trucks. Further details on the simulation methodology can be found in an accompanying report, providing a deeper examination on the technology challenges and opportunities of battery-electric tractor-trailers in the European Union (Basma et al., 2021).

Figure 2 shows the results of the vehicle model simulations. The fuel consumption of the diesel truck, the electric energy consumption of the battery-electric truck, and the electricity-equivalent energy consumption of the diesel truck are all estimated for two model years 2020 and 2030. Several payloads are also considered in the simulation, namely a reference payload at 19.3 tonnes, a low payload at 2.6 tonnes, and a combined payload defined as 70% reference payload—30% low payload, as per the official provisions set by the HDV CO_2 standards, EU Regulation 2019/1242 (Rodríguez, 2019). The energy efficiency of both tractor-trailers increases substantially between 2020 and 2030, at an approximate rate of 3% per year. This progress in efficiency is mainly the result of improvements in the aerodynamics, rolling resistance, and light-weighting—collectively known as the road-load—of both diesel and battery-electric tractor-trailers. The technology package has been documented in detail in a previous ICCT publication (Delgado et al., 2017).[3]

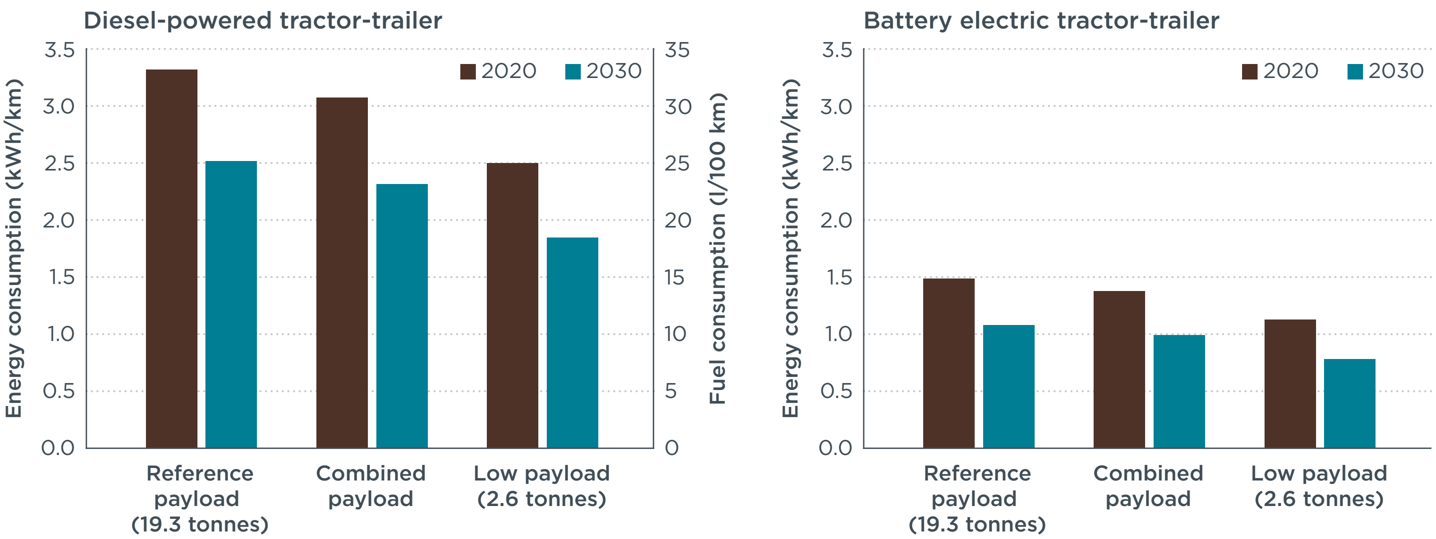

Figure 2. Fuel and energy consumption of the tractor-trailers analyzed for the model years 2020 and 2030 over different payloads.

The fuel consumption of the diesel truck over the long-haul cycle and the combined payload was estimated at 30.7 l/100 km for the 2020 model and 23.2 liter/100 km for the 2030 model, approximately a 25% reduction.[4] The magnitude of this reduction is in line with what would be required to meet the 2030 targets set by the HDV CO_2 standards, while making use of the regulatory flexibilities and incentives.[5] In the light

3 See 27%-reduction package in Figure ES 1 of the referenced publication.

4 The combined payload results weight the reference payload with 70% and the low payload with 30%. This follows the provisions introduced by the HDV CO_2 standards, EU Regulation 2019/1242.

5 These flexibilities and incentives include the use of banked credits and the zero- and low-emission vehicle incentives among others.

of the various announcements of vehicle manufacturers for the deployment of zero-emission trucks to meet the 2030 CO_2 targets, the diesel fuel consumption modeled in this paper represents what could be expected under the current stringency of the HDV CO_2 standards.

The energy consumption of battery-electric tractor-trailers, under the aforementioned driving and payload conditions, was estimated at 1.38 kWh/km for the 2020 model and 0.99 kWh/km for the 2030 model, a 28% decrease. This significant advance in energy efficiency is expected to happen in the absence of energy efficiency standards, as battery-electric vehicles will profit from the deployment of road-load improvements in other vehicle segments and will benefit from the rapid improvement in battery energy density and weight. The reported energy efficiency values in other studies (refer to Table 1) are in-line with the presented energy consumption values in this report. Figure 3 shows the nominal battery energy capacity in kWh used in the analysis of the battery-electric truck, throughout the different model years considered and at reference payload. These values were defined to meet a minimum range of 500 kilometers without charging the battery. More details regarding the required battery size as a function of the truck driving range and use case can be found in Basma et al. (2021). Currently, the Futuricum truck, based on the Volvo FH truck series, is the only truck equipped with a 900-kWh battery to cover a 500-km driving range (Futuricum, 2021).

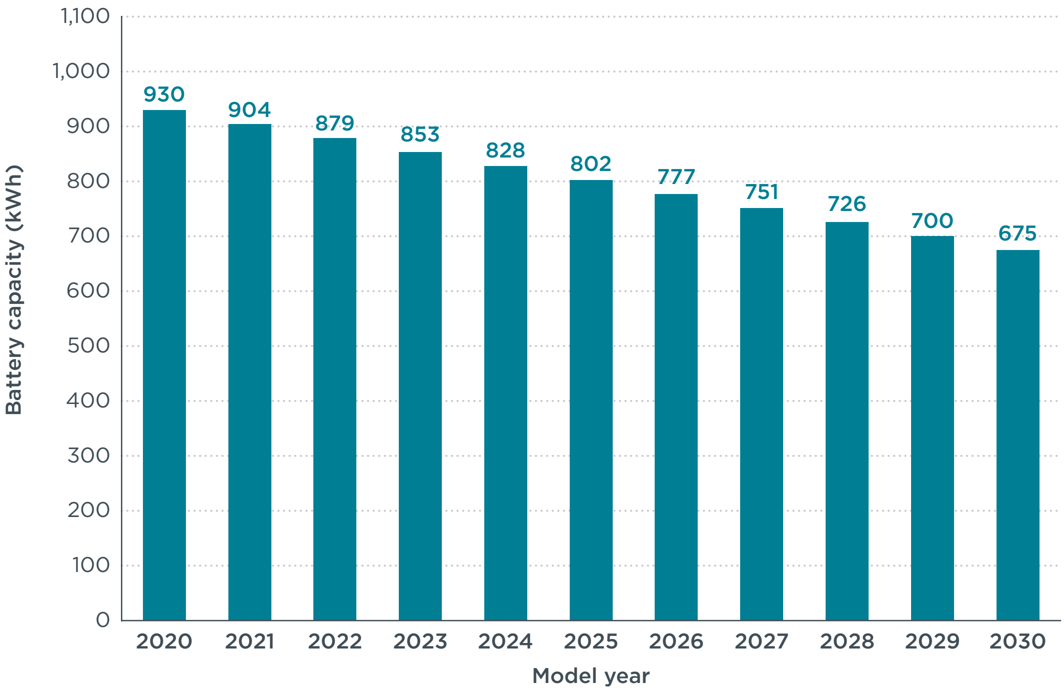

Figure 3. Battery energy capacity needed for each model year to meet the minimum single-charge range of 500 km at reference payload

FIXED COSTS

This section explains the assumptions made for the parameters of the TCO model that are independent of the distance traveled by the vehicle. They include the vehicle purchase, interests on loans, registration and ownership taxes, and annual fees for road use, where applicable. Vehicle insurance is excluded from the analysis as there are still lots of uncertainties regarding insurance premiums for BETs in the EU.

Vehicle purchase

Based on publicly available market data, the price of a 2020 diesel tractor-trailer is estimated at €100,000, with a baseline trailer price of €33,000, for a total of €133,000 for a 2020 diesel tractor-trailer. The diesel tractor price reflects that of 350 kW, in a 4×2 configuration equipped with a sleeper cab (Lastauto Omnibus, 2017). The baseline trailer price is for a new three-axle, six-tire, 13.65-meter, curtain-sider trailer (Lastauto Omnibus, 2017). Given that truck and trailer prices have remained relatively stable for the past few years, they are deemed representative of 2020 as well.[6] VAT is excluded from this study as it is a pass-through cost, and fleets can reclaim any VAT expenses when buying commercial vehicles.

The price for the subsequent model years is adjusted upward to account for the technology deployment required to improve the fuel consumption, as outlined in the previous section, and to meet future pollutant emission standards. Cost curves previously developed by ICCT (Meszler et al., 2018) were used to estimate the price increase from fuel efficiency technologies. The price increase from emission control technologies to meet future Euro VII standards has also been quantified by the ICCT (Ragon & Rodríguez, 2021) and is assumed to apply from 2025 onward. The price increase from the additional technology deployment already includes a markup to account for expenditures in research and development, overhead, marketing and distribution, and profit margins. The price of a 2030 diesel tractor-trailer is estimated to be approximately €145,000.

To assess the price of the battery-electric truck, a detailed truck component teardown analysis was conducted for the ICCT by Ricardo Strategic Consulting to estimate the direct manufacturing costs (DMC) of battery-electric trucks. The truck base glider components DMC for the 2020 model year truck are summarized in Table 4, excluding battery and electric powertrain costs. These DMC are assumed to be constant between 2020 and 2030 except for the trailer price, which increases by €4,822 in 2030 (Meszler et al., 2018), reflecting the introduction of road-load technologies to improve the energy efficiency of the battery-electric truck. To estimate the retail price of the base glider, indirect costs should be considered as well as costs related to research and development, overhead, marketing and distribution, warranty expenditures, and profit markups. These indirect costs are estimated using indirect cost multipliers (ICMs). Indirect costs vary with the complexity of associated technology and are roughly estimated to range from 15% to 75% of direct manufacturing costs. The combination of direct and indirect costs results in the expected retail price contribution associated with a particular technology, excluding VAT. The ICMs used in this study, which are shown in Table 5, correspond to the *high technology complexity level*, as defined by the U.S. Environmental Protection Agency (EPA & NHTSA, 2016), and have been subjected to rigorous development and review. For the base glider components, ICM of complexity level "High 1" is considered.

6 2018 was the last year the comprehensive Lastauto Omnibus Katalog (Lastauto Omnibus, 2018) was published.

Table 4. 2020 BET base glider direct manufacturing costs

Component	Specifications	Cost multiplier (€/kW)	Total cost (€)
Chassis	—	—	25,375
Trailer	—	—	33,000
Power electronics	350 kW	22.5/kW	7,875
On-board charger	44 kW	60/kW	2,640
Air compressor	6 kW	1,250/kW	7,500
Steering pump	9 kW	240/kW	2,160
Air-conditioning	10 kW	58/kW	580
Heater	10 kW	63/kW	630
Thermal management	350 kW	18/kW	6,300
Total cost	**—**	**—**	**84,685**

Notes: Original costs data are expressed in U.S. dollars (USD), a currency exchange rate of 1 EUR = 1.2 USD is considered in this study. The chassis includes axles, suspension, wheels, steering, and cab exteriors and interiors.

Table 5. Indirect cost multipliers for technologies with a high technology complexity level

Complexity level	ICM	2020 (near term)	2030 (long term)
High 1	Warranty costs	0.073	0.037
	Nonwarranty costs	0.352	0.233
	Total	**0.425**	**0.27**
High 2	Warranty costs	0.084	0.056
	Nonwarranty costs	0.486	0.312
	Total	**0.570**	**0.368**

The electric powertrain, in particular the battery, has a major contribution to the retail price of the battery-electric truck. We apply estimates developed by Ricardo Strategic Consulting for the ICCT to estimate the direct manufacturing cost of the electric drive, including the electric motor, inverter, and transmission between 2020 and 2030. The DMC of the e-drive is estimated to be $82/kW in 2020, decreasing to only $18/kW in 2030. The respective retail price estimates for a 350-kW electric powertrain in 2020 and 2030 are calculated using ICM of complexity level High 1, as described in Table 5.

Three scenarios were considered for the DMC of the heavy-duty battery—expressed in EUR/kWh—taken from publicly available sources for 2019 (Frith, 2020) and forecasted based on a previous ICCT analysis (Lutsey & Nicholas, 2019). While the DMC of battery cells has dropped significantly in the past years, there are important differences at the battery pack level between heavy- and light-duty vehicles, such as the energy-to-power ratio, durability, voltage level, power output, thermal management, and modularization. As a result, battery manufacturers for heavy-duty application currently serve a niche, but growing, market in Europe, leading to a pack-to-cell costs ratio in heavy-duty vehicles above 2, whereas in light-duty vehicle applications this is only 1.3 (Frith, 2020). The battery pack DMC used in this study is shown in Figure 4.

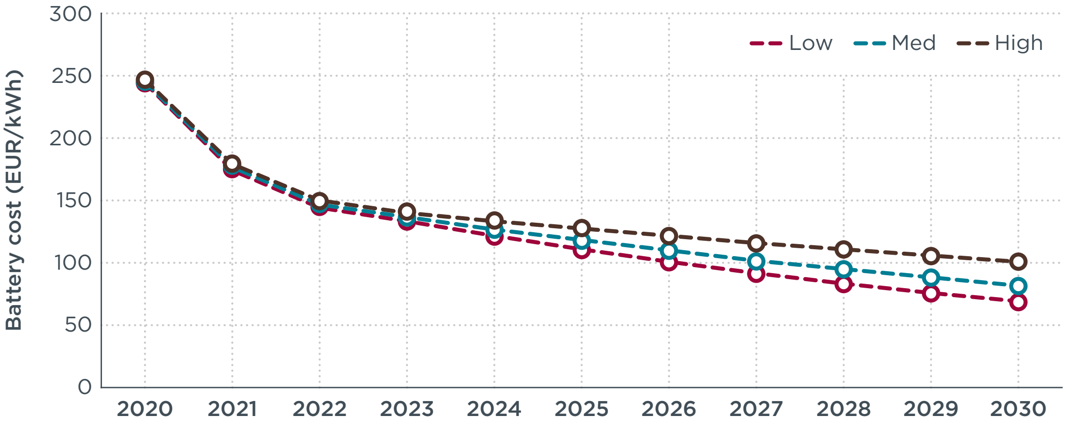

Figure 4. Three scenarios considered for the direct manufacturing costs of heavy-duty battery packs

The retail price evolution of the diesel and battery-electric tractor-trailers in the period 2020 to 2030 is shown in Figure 5 considering ICMs. Unless otherwise stated, the medium price scenario is used in the remaining sections of this paper.

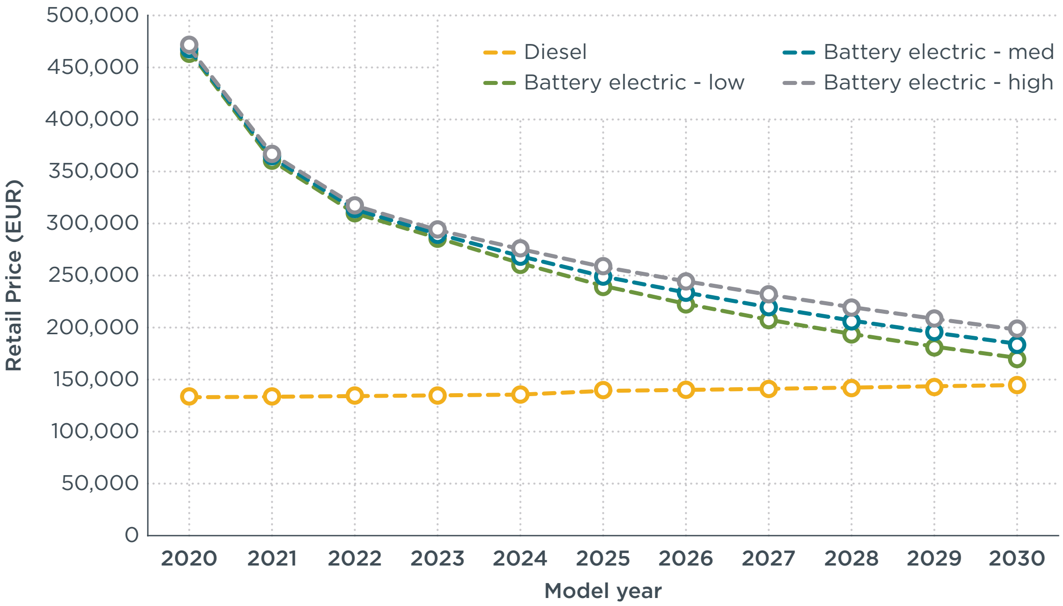

Figure 5. Estimated retail prices of battery-electric and diesel tractor-trailers in the 2020–2030 period

Truck financing and residual value

The financing of the vehicle purchase assumes that the loan term is equal to the analysis period (5 years) with an interest rate of 2% and that the installments are paid at the beginning of each period (year).

At the end of the analysis period, the salvage value was estimated based on the remaining service life. In a similar analytical approach to Feng & Figiliozi (2012), the truck depreciation, excluding the battery, is considered to be composed of a fixed depreciation rate at 7.5% per year (Gerber Machado et al., 2021) and a variable depreciation rate dependent on the annual vehicle kilometers traveled (VKT). The annual VKT-dependent depreciation rate is tuned so that the residual value of the truck is zero after a certain cumulative VKT. The lifetime VKT of a tractor-truck in the EU ranges between 1.02 and 1.49 million km, according to (Meszler et al., 2018), and based on this lifetime VKT, the resulting residual value of the truck after of 5 years of operation ranges between 20% and 38%. An average value of 30% is considered in this study. This depreciation is higher than the estimates used by the Joint Research Centre of the European Commission in the regulatory impact assessment (Krause & Donati, 2018). The latter estimates the residual value after 5 years at 56%.

To estimate depreciation of the electric tractor-trailer, the battery depreciation was estimated separately from the rest of the truck. The battery end-of-life was estimated at 1,500 cycles, which corresponds to a 20% loss in its original charge capacity and is roughly equivalent to 5 years of operation (Burke & Sinha, 2020). Thus, there is no need for any battery replacement from a first-user perspective. The battery estimated residual value for second-life applications is assumed to be 15% of the battery original cost (Burke & Fulton, 2019). The electric truck depreciation excluding the battery is assumed to be the same as diesel trucks at 30% after 5 years.

Registration and ownership taxes

Transport taxes and charges in this report are all taken from Schroten et al. (2019), unless otherwise specified. Vehicle taxes are classified under two categories:

» Acquisition and registration

» Ownership

Table 6 shows the registration and ownership taxes imposed in each country. The registration is a one-time fee charged at the time of purchasing the vehicle. The ownership tax, which ranges from €550 to €1,375 per year, should be paid annually by the vehicle owner. The motoring taxes are discussed in the operational costs section under diesel and electricity prices. Data provided in Table 6 are based on Schroten et al. (2019), except for Germany as the German Ministry of Finance publishes the annual ownership taxes on its website (BDF, 2021).

Table 6. Registration and ownership taxes imposed

Country	Registration (€)	Ownership (€/year)
Germany	0	929
Spain	0	850
France	800	950
Italy	1,500	1,000
Netherlands	0	1,375
Poland	290	1,300
United Kingdom	0	550

Vignette

The vignette is a fixed annual road-use charge, regulated through the Eurovignette Directive, which was first introduced in 1999 and revised in 2021 (European Council, 2021). HDVs with a gross vehicle weight of a minimum 12 tonnes must buy the vignette to use motorways and toll highways in some countries. Only two of the countries analyzed in this study— the Netherlands and the United Kingdom —use a time-based system of road-use charging, imposing €1,250/year and €1,000/year charges, respectively (Eurovignette.org, 2020; UK Department for Transport, 2018). However, the Netherlands is moving toward eliminating vignettes and imposing a distance-based road toll in 2023 (Ministry of Infrastructure and Water Management, 2019). The recent revision of the Eurovignette Directive requires the transition from time-based to distance-based charging in all EU member states that currently apply this system.

OPERATIONAL COSTS

The annual truck operational costs are highly dependent on the distance covered by the trucks each year. Therefore, the TCO calculations are highly sensitive to the choice of the VKT. The annual VKT of a typical long-haul tractor-trailer is highest during the first year of ownership and then drops over time as the vehicle ages. The age-dependent VKT for long-haul tractor-trailers is estimated from the EU TRACCS database (Emisia SA et al., 2013). TRACCS does not explicitly distinguish short- and long-haul statistics, instead treating VKT and population statistics for tractor-trailers in the aggregate. This has the effect of underestimating long-haul tractor-trailer VKT. Therefore, TRACCS data on the trip length distribution was used to adjust the VKT to reflect the long-haul use-case analyzed in this paper (Meszler et al., 2018).

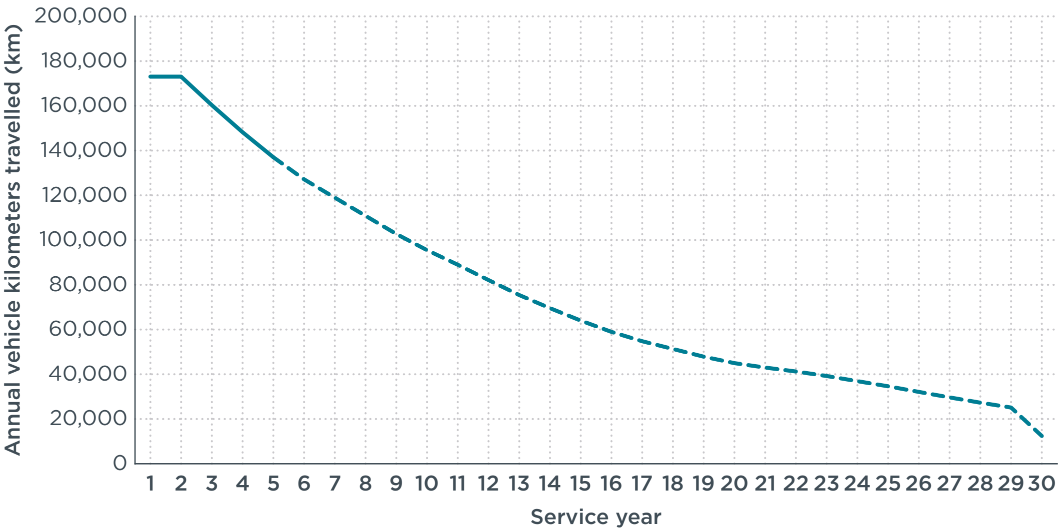

Figure 6. Annual vehicle kilometers traveled versus truck age

Distance-based road tolls

Several European countries apply road-use charges based on the distance driven in kilometers, the emission category of the vehicle, and the number of axles. These distance-based road tolls will be regulated by the recently agreed-on revision of the Eurovignette Directive (European Council, 2021).

The United Kingdom and the Netherlands are the only countries that currently do not impose a kilometer-based road charge; however, the Netherlands is eliminating vignettes in favor of imposing distance-based charges starting 2023 at an average of 15 EUR cents/km depending on the weight and class of the truck (Ministry of Infrastructure and Water Management, 2019). Among the countries that charge road tolls, Poland had the lowest charge with 5.5 EUR cents/km and France had the highest charge with 32 EUR cents/km. Also, it was assumed that 80 percent of the VKTs are on roads that charge tolls. However, it should also be noted that there are different approaches for collecting road charges among European countries. In some countries, such as France, Italy, and Spain, the road tolls are given to concession consortiums, with agreements that typically run for decades. In other countries, such as Germany, it is through a network-wide tolling system. Poland has a mix of concessions and distance-based road tolling. Table 7 shows a summary of all the distance-based charges.

Table 7. Road tolls in the countries studied

Country	Road toll (€/km)	Source
Germany	0.187[a]	(Toll Collect, 2020)
Spain	0.160	(Schroten et al., 2019)
France	0.320	(Schroten et al., 2019)
Italy	0.190	(Autostrade per l'Italia, 2020)
Netherlands	0.150	(Ministry of Infrastructure and Water Management, 2019)
Poland	0.055	(Ministerstwo Infrastruktury, 2020)
United Kingdom	0	(Schroten et al., 2019)

[a] Road tolls for electric vehicles in Germany are waived entirely (BMVI, 2021).

Maintenance costs

Table 8 shows the maintenance costs and the items considered for each truck type. The total maintenance cost is composed of several components, including lubricants, oil changes, AdBlue refilling, repairs and preventive maintenance, and tires. All diesel truck maintenance cost data are extracted from *Lastauto Omnibus* (2017), except for tractor-trailer tire maintenance data as they were extracted based on costs informed by German consumer publications and are assumed to also apply to the other countries analyzed (Braun, 2016). As for BETs, there are no maintenance costs related to oil changes and AdBlue refilling, and the repair and preventive maintenance costs are assumed to be 33% less compared to diesel trucks as reported by Kleiner & Friedrich (2017). Tire cost is assumed to be the same as for diesel trucks.

Thus, the total maintenance cost for diesel tractor-trailers is estimated at €18.5/100 km, while battery-electric tractor-trailers total maintenance costs are estimated at €13.24/100 km, approximately 30% lower than their diesel counterpart.

Table 8. Breakdown of maintenance cost for each truck type

Item	Diesel truck	Battery-electric truck
	Cost in €/100 km	
Lubricants, oils	0.75	—
AdBlue refilling	0.55	—
Repair and preventive maintenance	12	8.04
Tires: front and driven axles	2.47	2.47
Tires: trailer	2.73	2.73
Total	**18.5**	**13.24**

Diesel prices

The price of diesel consists of multiple components: crude oil price, refining costs, distribution costs, excise duties (fixed), and VAT. Table 9 shows the latest diesel prices across the seven countries considered in this study (DKV, 2020). Fleets can request a refund for the VAT paid on fuel; therefore, VAT is not included in cost calculations in this study. Additionally, some European countries offer reimbursement for a part of the excise duty (FuelsEurope, 2019); this refund was also included in the model.

Table 9. Summary of diesel prices including refunds (EUR/liter) in 2020

Country	Gross price (€)	VAT rate	VAT (€)	Excise duty (€)	Excise duty refund in 2020 (€)	Net price with tax refunds (€)
Germany	1.08	19%	0.172	0.470	0	0.905
Spain	1.03	21%	0.179	0.379	0.049	0.805
France	1.24	20%	0.207	0.594	0.157	0.875
Italy	1.31	22%	0.236	0.617	0.214	0.860
Netherlands	1.28	21%	0.221	0.503	0	1.055
Poland	0.96	23%	0.179	0.337	0	0.776
United Kingdom	1.31	20%	0.219	0.580	0	1.093

Diesel price projection for the 2020–2030 time frame is highly uncertain, mainly driven by variations in crude oil price. To overcome this level of uncertainty, we consider several scenarios for the diesel fuel price projection between 2020 and 2030.

Electricity prices and charging infrastructure

This section explains the modeling approach and the assumptions made for estimating the final average levelized electricity prices for electric trucks in each considered EU member state. The electricity price was estimated based on two components: the electricity price charged by the utilities and the charging station infrastructure costs.

Electricity prices charged by utilities

The electricity prices were collected from the European Commission public database (European Commission, 2020a). There are several bandwidths for nonresidential electricity prices in each country depending on the annual consumption, ranging between bandwidth IA (less than 20 MWh per year) to IG (more than 150,000 MWh per year). The unit price of electricity varies quite significantly across the bandwidths. For example, the difference in the EU average electricity prices between bandwidths IB and ID—which is the range of bandwidths of interest in this study—is around 38%. Although electricity prices for nonresidential users do vary during the day—mainly a day tariff and a night tariff—the available official EU public database does not provide such data. Table 10 shows the electricity prices for bandwidths IB and ID in each of the seven countries: the energy and supply price, the network costs, VAT, and other taxes and levies.

Table 10. Electricity prices (€/kWh) for bandwidth IB and ID in each country 2020 prices

Country	Bandwidth	Energy and supply	Network costs	Taxes, fees, levies, and charges	VAT (recoverable)	Total (w/o VAT)	Total (w VAT)
Germany	IB	0.0455	0.0549	0.1389	0.0356	0.2037	0.2393
France	IB	0.0626	0.0424	0.0559	0.0263	0.1346	0.1609
United Kingdom	IB	0.0801	0.0416	0.0793	0.0321	0.1689	0.201
Italy	IB	0.0732	0.0252	0.1038	0.0325	0.1697	0.2022
Netherlands	IB	0.0536	0.0278	0.0735	0.0269	0.128	0.1549
Spain	IB	0.0524	0.0498	0.0768	0.0311	0.1479	0.179
Poland	IB	0.0571	0.0446	0.058	0.0298	0.1299	0.1597
EU average	IB	0.0571	0.0432	0.0821	0.0297	0.1527	0.1824
Germany	ID	0.038	0.0338	0.1193	0.0283	0.1628	0.1911
France	ID	0.0509	0.0178	0.0305	0.016	0.0832	0.0992
United Kingdom	ID	0.0656	0.0272	0.0773	0.0276	0.1425	0.1701
Italy	ID	0.0671	0.0155	0.0628	0.0159	0.1295	0.1454
Netherlands	ID	0.0474	0.0162	0.055	0.0206	0.098	0.1186
Spain	ID	0.0475	0.0182	0.036	0.0176	0.0841	0.1017
Poland	ID	0.051	0.0188	0.0488	0.0222	0.0964	0.1186
EU average	ID	0.0493	0.0221	0.0595	0.0202	0.1107	0.1309

Like diesel fuel prices, projections for electricity prices during the 2020–2030 time frame involve lots of uncertainties, and the reported values in the literature are highly dispersed. Thus, several scenarios for electricity prices have been considered between 2020 and 2030, as will be highlighted in the results section.

Charging station infrastructure costs

The charging station infrastructure costs consist of capital expenditures (CAPEX) and operating expenses (OPEX), where the charging station owner-operator recuperates CAPEX and OPEX by charging an overhead fee on top of the electricity price, which determines the final energy price for consumers. It is assumed that the stations are owned by the private sector.

It is assumed that the truck leaves the depot with a fully charged battery, travels for a maximum of 4.5 hours with a minimum of 45 minutes rest as mandated by European regulations (European Commission, 2006), and reaches its destination, where it charges overnight. It is also assumed that the midway charging is done at a commercial fast charging station with 350-kW power capacity and charging at the destination is done using 100-kW chargers. To reduce the truck's total cost of energy on each daily trip while always maintaining a minimum 15% battery charge, it is determined that 20% of the total electricity needed for each day should be charged at the commercial 350-kW fast charging station and the rest at the destination's overnight charging station.

To estimate the charging station CAPEX, it is assumed that the charging stations will be accommodated in existing depots and vestibules that do not incur any construction or renovation costs, and thus only chargers' hardware and installation costs are considered in this study. Chargers' hardware and installation costs in 2020 and 2030 were adopted from recent data published in the Alternative Fuels Infrastructure Regulation (AFIR) announced on July 2021 (European Commission, 2021b). The 350-kW charger's unit cost decreases from 230,000 EUR in 2020 to 164,836 EUR in 2030. The annual charging station OPEX—which includes rent, maintenance, network and operation, customer support, and business licenses—are estimated at 1.2% of the charging station CAPEX, according to an AFIR impact assessment study (European Commission, 2021b). As for the overnight charging station, the unit cost of 100-kW chargers was estimated to decrease from 67,501 EUR in 2020 to 48,888 EUR in 2030. It is assumed that each station is equipped with 10 chargers with a 95% availability, that is, 5% of the time the charger will be out of service due to repairs and maintenance and the CAPEX are multiplied by the chargers' availability ratio (1.05 in this case).

The overhead charge is calculated by adding the net present value of CAPEX and OPEX divided by the total electricity consumption during the full-service life of the charging station. The total electricity consumption of the charging station is dependent on its chargers' utilization ratio during the day. The latter is defined as the average daily total electricity consumption over the maximum charging capacity of the station (24 hours at maximum charging power). Therefore, the higher the utilization ratio is, the lower are the overhead costs for a constant CAPEX. For this study it is assumed that the utilization ratio for fast chargers is 1% in 2020, increasing to 16% in 2030. These values were assumed to be 33% for the 100-kW depot chargers in both 2020 and 2030. Also, it was assumed that the utilization ratio follows a logarithmic growth function, with higher growth rates in the first few years that taper off with time. The chargers' efficiency is assumed to be 95% for both the fast 350-kW and the depot 100-kW chargers.

To estimate the charging station overhead fee, a 15-year service life was assumed for each station and the total CAPEX—with an internal rate of return of 9.5%—and OPEX during those 15 years were divided by the total electric energy throughput.

The overhead fees and the detailed analytical approach used to estimate those fees are presented in Table 11 and Table 12 for the fast and overnight charging stations, respectively.

Table 11. Capital and operational cost of a fast charging station

Fast charging station				
CAPEX				
ID	**Parameter**	**2020**	**2030**	**Equation**
A	Number of chargers	10	10	—
B	Charging power (kW)	350	350	—
C	Hardware costs per unit (EUR)	170,000	116,455	—
D	Installation costs per unit (EUR)	60,000	48,381	—
E	Chargers' availability	95%	95%	—
F	Station power capacity (kW)	3,500	3,500	B × A
G	Hardware costs total (EUR)	1,700,000	1,164,550	C × A
H	Installation costs total (EUR)	600,000	483,810	D × A
I	**CAPEX (EUR)**	**2,415,000**	**1,730,778**	**(G + H) × (1 + 1 - E)**
J	CAPEX per charger (EUR)	241,500	173,078	I / A
OPEX				
K	OPEX share of CAPEX	1.2%	1.2%	—
L	**OPEX (EUR/year)**	**28,980**	**20,769**	**I × K**
Overheads				
M	Utilization ratio	1%	16.04%	—
N	Number of weeks in use	52	52	—
O	Number of days per week in use	6	6	—
P	Charger's efficiency	95%	95%	—
Q	Internal rate of return	9.5%	9.5%	—
R	Station service life (years)	15	15	—
S	Annual electricity consumption (MWh)	276	4,425	F × (M × N × O × 24) / (P × 1000)
T	Corresponding bandwidth	IB	ID	*function* (S)
U	OPEX overhead (EUR/kWh)	0.1050	0.0047	L / (S × 1000)
V	CAPEX annual loan payments (EUR)	308,501	221,096	$I \times Q \times (1 + Q)^R / [(1 + Q)^R - 1]$
W	CAPEX overhead (EUR/kWh)	1.1183	0.0500	V / (S × 1000)
X	**Overheads (EUR/kWh)**	**1.2233**	**0.0547**	**U + W**

Table 12. Capital and operational cost of an overnight charging station

Overnight charging station				
CAPEX				
ID	**Parameter**	**2020**	**2030**	**Equation**
A	Number of chargers	10	10	—
B	Charging power (kW)	100	100	—
C	Hardware costs per unit (EUR)	49,063	33,823	—
D	Installation costs per unit (EUR)	18,438	15,065	—
E	Chargers' availability	95%	95%	—
F	Station power capacity (kW)	1,000	1,000	B × A
G	Hardware costs total (EUR)	490,630	338,230	C × A
H	Installation costs total (EUR)	184,380	150,650	D × A
I	**CAPEX (EUR)**	**708,761**	**513,324**	**(G + H) × (1 + 1 - E)**
J	CAPEX per charger (EUR)	70,876	51,332	I / A
OPEX				
K	OPEX share of CAPEX	1.2%	1.2%	—
L	**OPEX (EUR/year)**	**8,505**	**6,160**	**I × K**
Overheads				
M	Utilization ratio	33%	33%	—
N	Number of weeks in use	52	52	—
O	Number of days per week in use	6	6	—
P	Charger's efficiency	95%	95%	—
Q	Internal rate of return	9.5%	9.5%	—
R	Station service life (years)	15	15	—
S	Annual electricity consumption (MWh)	2,627	2,627	F x (M × N × O × 24) / (P × 1000)
T	Corresponding bandwidth	ID	ID	*function* (S)
U	OPEX overhead (EUR/kWh)	0.0032	0.0023	L / (S × 1000)
V	CAPEX annual loan payments (EUR)	90,540	65,574	$I \times Q \times (1 + Q)^R / [(1 + Q)^R - 1]$
W	CAPEX overhead (EUR/kWh)	0.0345	0.023	V / (S × 1000)
X	**Overheads (EUR/kWh)**	**0.0377**	**0.0273**	**U + W**

Finally, the levelized electricity prices, including energy tariffs, network costs, taxes, and infrastructure (overhead charges), are presented in Figure 7. The overhead charges presented in this chart are average charges between the fast 350-kW and depot 100-kW charging stations, where the former was assumed to supply 20% of the total truck daily energy needs and the rest is supplied by the depot 100-kW charging station.

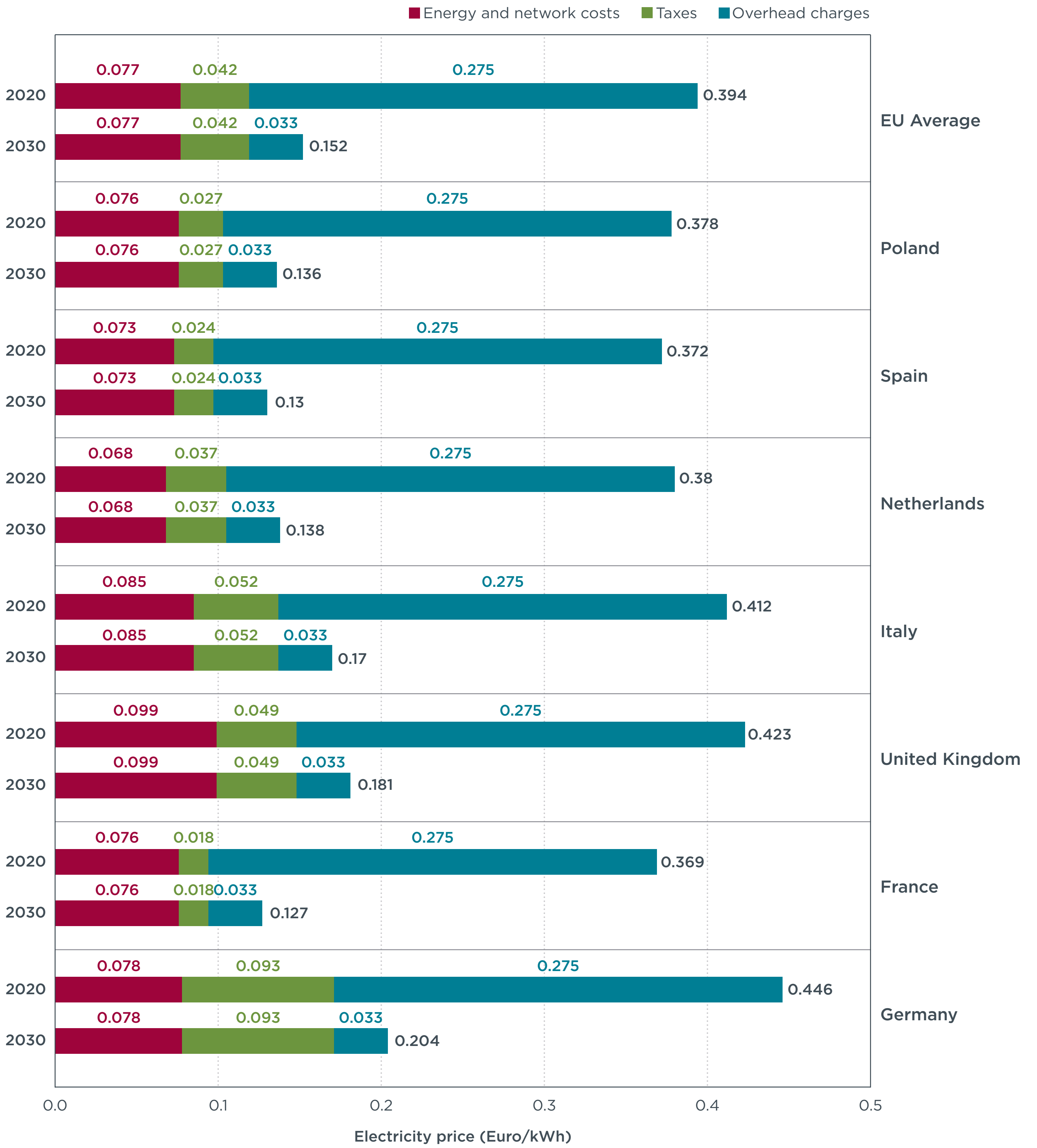

Figure 7. Summary of electricity prices components charged by charging stations operators

RESULTS AND DISCUSSION

KEY FINDINGS

In this section, the TCO of the BETs and diesel trucks across the considered countries is compared without any policy interventions to properly compare the technology costs from a first-ownership perspective, even though some policy interventions are already in place in some EU member states, as will be discussed in the *Analysis of Policy Measures* section.

Two scenarios are considered in this section:

1. A baseline scenario where the diesel fuel and electricity prices for each member state are fixed between 2020 and 2030, considering 2020 prices.
2. A scenario where the diesel fuel and electricity prices vary during the 2020–2030 time frame.

Baseline scenario: Fixed diesel fuel and electricity prices between 2020 and 2030

Figure 8 shows the net present value of BETs versus diesel trucks for different model years between 2020 and 2030 considering fixed diesel fuel and electricity prices in the 2020–2030 time frame. Data points above the diesel truck TCO line—which represents the TCO parity line in this case—correspond to model years where BETs are more expensive than their diesel counterparts. Across all countries considered in this study, the TCO of BETs decreases between 2020 and 2030, driven by the decrease in the truck purchase price due to battery cost reduction, and by the reduction in the truck operating costs due to truck efficiency improvement resulting in lower energy costs. In addition, the reduction in the electricity overhead charges related to the charging infrastructure also contribute to the reduction in the TCO of BETs. Diesel trucks witness a stable TCO between 2020 and 2030 with a slight reduction due to efficiency improvement resulting in lower operating costs, although the purchase cost of diesel trucks slightly increases between 2020 and 2030 as discussed in the *Vehicle purchase* section.

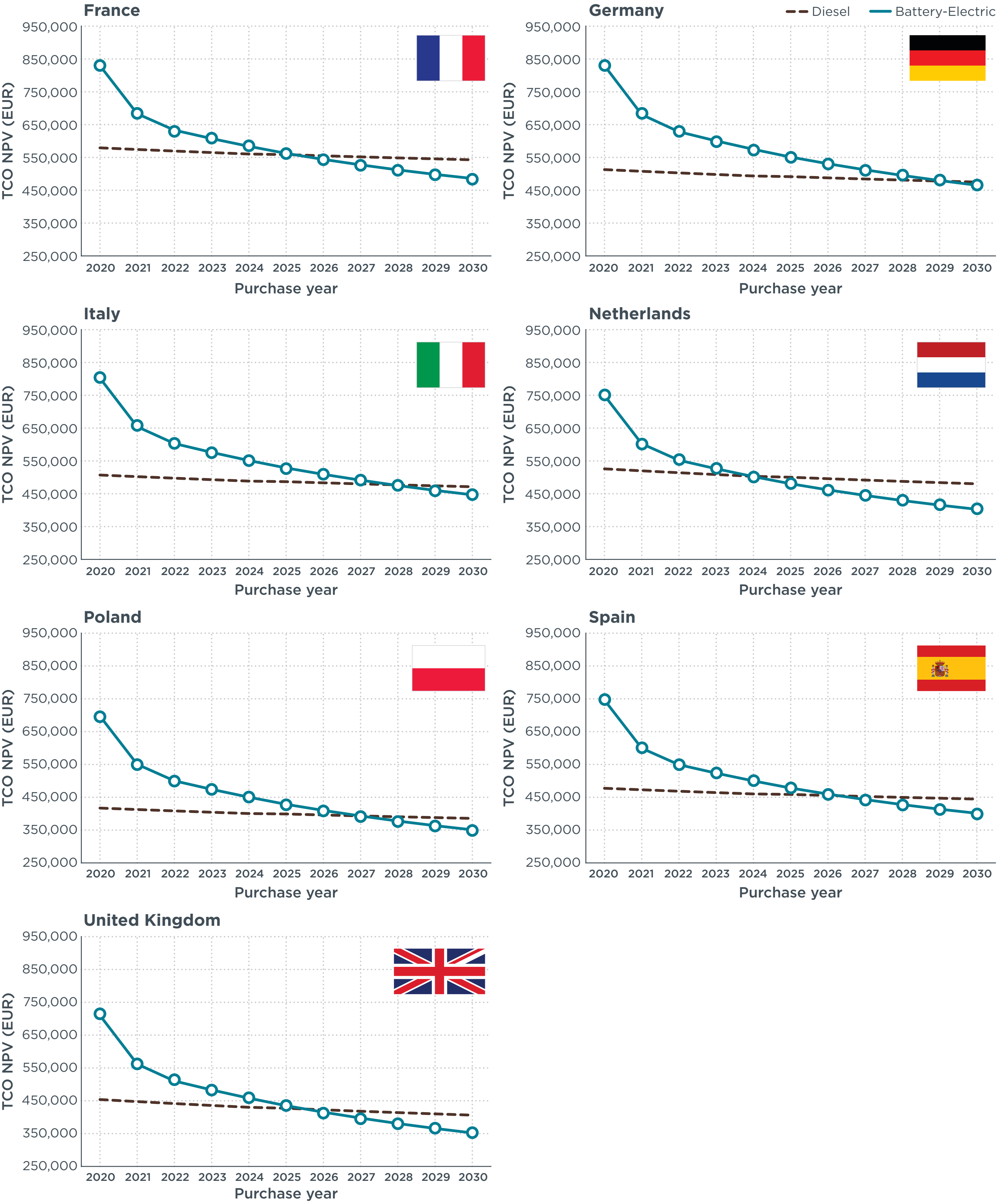

Figure 8. TCO of BETs and diesel trucks (NPV) as a function of year of purchase, from the first ownership perspective (5 years) considering fixed diesel fuel and electricity prices for the 2020–2030 time frame

Table 13 shows the year in which TCO parity between the two trucks is achieved for each of the countries considered in the study. BETs achieve TCO parity with their diesel counterparts during this decade in all the countries considered in this study, though with differences in the TCO parity year. The Netherlands will be the first country where TCO parity between BETs and diesel trucks will be achieved in 2024 without introducing any policy measures or incentives. Germany and Italy have the longest time frame across all seven countries considered, with TCO parity achieved in 2029 and 2028, respectively. BETs operating in other countries can achieve TCO parity around the middle of the decade. More detailed insights regarding the differences in BETs' TCO parity time among the considered countries is presented in the *Country-specific analysis* section.

Table 13. The year in which TCO parity is achieved between BETs and diesel trucks without any policy intervention

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
No incentives	2025	2029	2028	2024	2027	2027	2026

Variable diesel fuel and electricity prices between 2020 and 2030

The baseline scenario analysis conducted in the previous section considers fixed diesel fuel and electricity prices in the 2020–2030 time frame. In this section, diesel fuel and electricity prices are considered to vary at an annual rate ranging between -3% and 3%, highlighting their impact on the TCO parity between BETs and diesel trucks. This range is inspired by current diesel fuel prices projection for the 2020–2030 time frame as they estimate a 2.5% to 3% annual increase in crude oil prices as reported by EIA (2020) and Deloitte (2020) respectively.

As shown in Figure 9, the variations in diesel fuel and electricity prices have a significant impact on the year BETs achieve TCO parity with diesel trucks. In the case of France, for fixed electricity prices (0% electricity prices annual increase), the TCO parity time between the two truck types could range from 2024 to 2028, depending on the annual evolution of diesel fuel, assessed from 3% to -3% change per year. On the other hand, for fixed diesel fuel prices in the case of France (0% diesel fuel prices annual increase), TCO parity time ranges between 2025 and 2027 if electricity prices annual increase ranges between -3% and 3%. It is worth mentioning that a 3% annual increase in electricity prices is rather an extreme estimate, which is unlikely to happen, yet the analysis still provides important insights on TCO parity year sensitivity to such extreme scenarios.

The TCO parity time sensitivity to diesel fuel and electricity prices variation is different for each country; however, TCO parity time is more sensitive to variation in the diesel fuel prices across all countries. This is clear from the slopes of the contour lines in Figure 9 as they are more inclined toward the electricity prices axes, implying less sensitivity to electricity prices. This can be explained by the fact that diesel trucks consume more energy per km when compared to BETs, making diesel trucks' TCO and the BETs' TCO parity time highly sensitive to diesel fuel prices.

In addition, for countries like the Netherlands and France, any combination of electricity and diesel fuel prices variation would still result in a TCO parity during this decade. Other countries may witness a delayed TCO parity time beyond this decade if some extreme and unlikely-to-happen scenarios are considered, such as a 3% annual increase in electricity prices accompanied with a 3% annual reduction in diesel fuel prices.

Even though energy price estimations involve a very high level of uncertainty, there are some estimates for the evolution of diesel fuel and electricity prices over the next decade. As mentioned earlier, current diesel fuel prices esimates for the 2020–2030 time frame report a 2.5% to 3% annual increase. As for electricity prices projections, the

European Commission expects stable electricity prices for the 2020–2030 time frame, as reported in the POTEnCIA Central Scenario study (Mantzos et al., 2019). Under these current estimates, BETs will achieve TCO parity 2 years earlier in most of the countries considered in this study—as early as 2023 for the Netherlands and 2024 for France—in comparison to the baseline scenario of fixed electricity and diesel fuel prices.

In most electricity and diesel fuel prices projection scenarios, BETs would still achieve TCO parity with their diesel counterparts but with a significant variation in the TCO parity year. This stresses the importance of establishing fiscal policies to subsidize electricity prices in the future or of imposing taxes on diesel fuel prices, which is discussed in the upcoming sections.

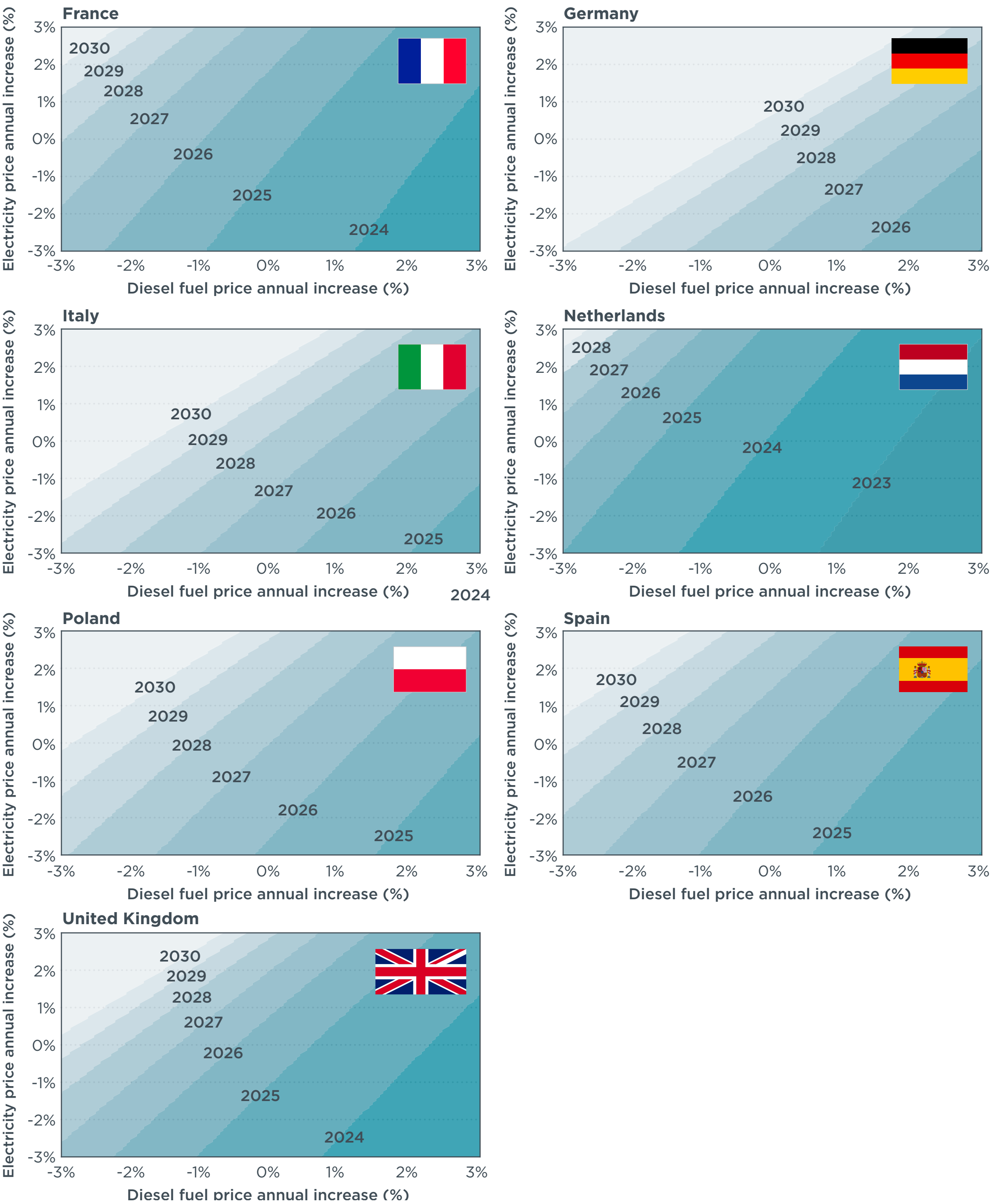

Figure 9. BETs and diesel trucks TCO parity under variable diesel fuel and electricity prices projection for the 2020–2030 time frame

ANALYSIS OF POLICY MEASURES

In this section the impacts of various policy measures that can be implemented to incentivize the transition to electric trucks are analyzed. For this purpose, the following list of policy measures were considered:

- Purchase premiums for electric trucks
- Exemption or reduction of road tolls for electric trucks
- Addition of CO_2 external cost to road tolls
- Inclusion of transport sector in the EU Emissions Trading System (ETS)
- Fiscal incentives for electricity prices
- Infrastructure incentives for electric trucks
- Policy package or the combination of the first four policy measures presented above, which are discussed later in the *Country-specific analysis* section

Purchase premiums

Public authorities often incentivize the adoption of alternative vehicle technologies by offering purchase premiums. The purchase incentives considered in the analysis are shown in Table 14.

Table 14. Summary of purchase incentives in the countries studied

Country	Incentive	Source
Germany	80% of cost difference to diesel truck capped at €450,000	(BAG, 2021)
Spain	€15,000	(IDAE, 2020)
France	€50,000	(Ministère de l'Économie, des Finances et de la Relance, 2020)
Italy	€20,000	(MIT, 2019)
Netherlands	set at 40% of the price difference between the BET price (with no incentive) and the diesel truck price	(Ministerie van Algemene Zaken, 2019)
Poland	30% of the price difference of BET (with no incentive) and diesel truck limited to €45,000 maximum	(Ministerstwo Aktywów Państwowych, 2019)
United Kingdom	€7,000[a]	(Department for Transport, 2020)

[a]The grant covers 20% of the purchase price, up to a maximum of £16,000 available only for the first 250 orders placed. A maximum grant rate of £6,000 will apply when that limit is exceeded (1 GBP = 1.16 EUR).

Table 15 shows the effect of the purchase premiums on the year of TCO parity between the two truck types. Purchase premiums are applied only to electric trucks, deducting a fixed amount from their purchase price. We assume that the currently applied purchase premiums stay in place for the entire 2020–2030 time frame, though one could expect a gradual decrease in these premiums until they are entirely phased out. For Germany, the generous purchase premiums offered result in a 7-year reduction of the time frame to achieve TCO parity. France and the Netherlands also offer high purchase premiums resulting in a 2-year reduction in the TCO parity time between both truck types. The purchase incentives offered in the United Kingdom are not large enough to change the time frame to TCO parity. For Poland, Spain, and Italy, this reduction is 1 year.

Table 15. The impact of purchase premiums on the year TCO parity is achieved between BETs and diesel trucks

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity with purchase premiums	2023	2022	2027	2022	2026	2026	2026

Exemption or reduction in road tolls

Germany exempts zero emission heavy-duty vehicles (ZE-HDVs) from road tolls. For other countries, we evaluated a 75% reduction in the road toll, in line with the adopted revision of the Eurovignette Directive. Table 16 shows how exempting or reducing road toll charges for BETs can substantially shorten the time frame for achieving TCO parity between electric and diesel trucks for most countries. The United Kingdom is the only exception since it does not impose distance-based road tolls and only has a small time-based road charge (vignette). Germany has the highest shift (5 years), followed by Italy, Spain, and France with 4 years. The reduction in time frame to reach TCO parity is 2 years for the Netherlands and 1 year for Poland.

Table 16. The impact of VKT road tolls reduction on the year TCO parity is achieved between BETs and diesel trucks (75% exemption for all countries, except for Germany at 100%)

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity with toll reduction	2021	2024	2024	2022	2026	2023	2026
Road toll reduction	75%	100%	75%	75%	75%	75%	75%

Addition of CO_2 external cost to road tolls

The Eurovignette Directive, which sets the regulatory framework at the EU level to charge heavy goods vehicles for the use of infrastructures, was recently amended to make progress in the application of the "polluter pays" and "user pays" principles. To account for the externalities due to CO_2 emissions, a reference road charge of 8 EUR cents/km is set for heavy goods vehicle with laden mass over 32 tonnes—like the tractor-trailer segment analyzed in this study—and 0 cents/km for zero-emission vehicles. The directive would also allow member states to apply higher external cost charges for CO_2 emissions, limited to twice the reference values, which is 16 EUR cents/km for trucks heavier than 32 tonnes (European Council, 2021). We assume that this policy is applied to 100% of the diesel truck VKT. This section investigates the impacts of implementing such policy.

As shown in Table 17, among the seven countries considered in this study, the addition of CO_2 external cost to road tolls at the reference value of 8 EUR cents/km results in a maximum of 3 years reduction in the time frame to reach TCO parity between electric and diesel trucks for Germany, Italy, Spain, Poland, and the United Kingdom and 2 years reductions for the Netherlands and France.

Table 17. The impact of adding CO_2 external cost to road tolls on the year TCO parity is achieved between BETs and diesel trucks

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity CO_2 charge of 8 EUR cents/km	2023	2026	2025	2022	2024	2024	2023
TCO parity CO_2 charge of 16 EUR cents/km	2022	2023	2022	2021	2022	2022	2022

A CO_2 charge of 16 EUR cents/km would lead to even greater changes in the year of TCO parity, helping BETs achieving TCO parity with their diesel counterparts as early as 2021–2023 for all countries considered in this analysis.

Although the absolute TCO reduction in Euros is the same for all countries under this policy intervention, how soon the TCO parity year is reached for BETs varies significantly from country to country. Country-specific cost components drive these different TCO gaps between BETs and diesel trucks.

ETS for transport

To accelerate the reduction of CO_2 emissions across Europe, the European Commission proposed—as part of the Fit for 55 packages—extending the European ETS to include transport and buildings. Emissions trading for the buildings and road transport sectors would be introduced through a separate but adjacent emissions trading system (European Commission, 2021b). Currently, Germany is the only EU member state to implement a carbon pricing system for transport as of 2021, adopting its fuel emissions trade law first proposed in 2019 (BMU, 2021). In 2021, the price is fixed at €25/tonne of CO_2 equivalent, which will increase to €55/tonne CO_{2e} by 2025. By 2026, a price corridor between €55 and €65/tonne CO_{2e} is to be implemented. Beyond 2026, a market price will be considered with the possibility of implementing a price corridor, which is to be decided in 2025 (Wettengel, 2021). Figure 10 shows the ETS for transport carbon prices implemented in Germany. Beyond 2026, we assume fixed prices at €65/tonne CO_{2e}.

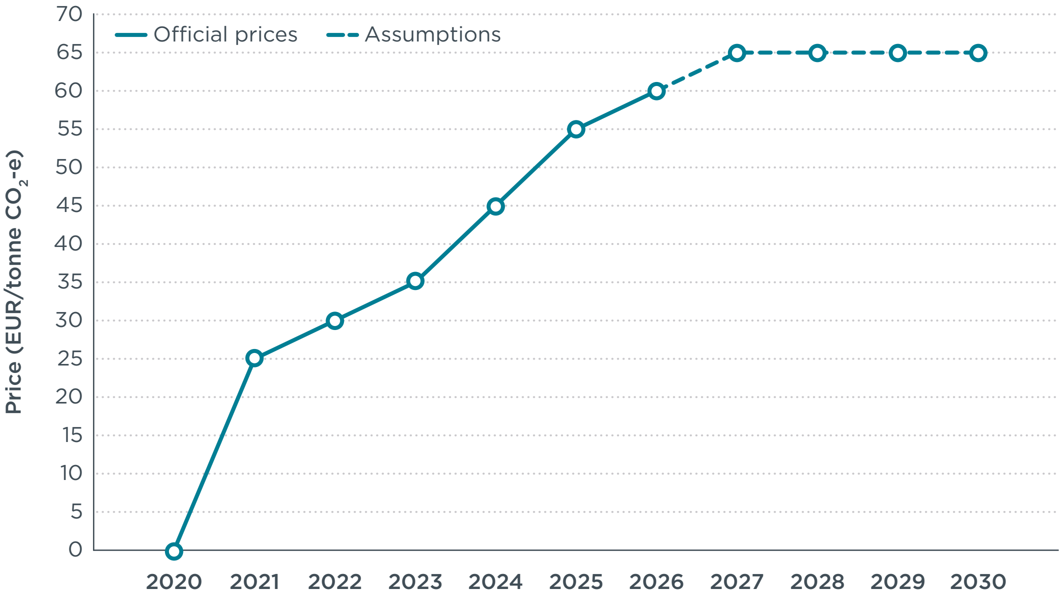

Figure 10. National transport carbon prices implemented in Germany (Wettengel, 2021)

In our modeling, due to the early stages of the regulatory process for setting the separate ETS for transport and buildings, we assumed that other EU member states considered in this study will impose carbon prices similar to Germany. The results presented below are only intended to illustrate the impact of the policy measure on TCO parity between BETs and diesel trucks. Extending the ETS to transport reduces the time span to reach TCO parity by 1 year for most of the considered countries in this study as shown in Table 18.

Table 18. The impact of ETS for transport on the year TCO parity is achieved between BETs and diesel trucks

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity ETS for transport	2024	2028	2026	2023	2026	2025	2025

Fiscal incentives for electricity prices

Nonrecoverable levies and surcharges are a significant component of the electricity prices in the considered EU countries, representing 19%–55% of the total electricity price, depending on the country. Currently, Germany records the highest share at 55%, whereas France records the lowest share at 19%. The EU average share of nonrecoverable levies and surcharges is around 27%. Those nonrecoverable levies and surcharges may include energy taxes, carbon taxes, climate-energy levies, and renewable energy surcharges (i.e., charges collected to promote renewable electricity production). Due to their significant contribution to the total electricity prices, and with the purpose of understanding the sensitivity of TCO parity to fiscal incentives for the use of renewable electricity in BET charging, this section examines the TCO impact of reducing those levies and surcharges by 50% of current values. This is intended as a sensitivity analysis only. The results are summarized in Table 19.

Table 19. The impact of reducing electricity nonrecoverable levies and surcharges by 50% on the year TCO parity is achieved between BETs and diesel trucks

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
Reduction in electricity levies and surcharges	2025	2026	2026	2023	2026	2026	2024

BETs operating in Germany benefit the most from this policy intervention as the TCO parity time is reduced by 3 years, from 2029 down to 2026. BETs operating in the United Kingdom realize a 2-year reduction in their TCO parity time relative to diesel trucks, while BETs operating in other countries realize a 1-year reduction only, if any. In France, such levies and surcharges are not very high, and thus this policy intervention has a negligible impact on TCO parity time of BETs relative to diesel trucks.

Infrastructure incentives for electric trucks

Acknowledging that infrastructure will play a vital role in any successful transition to zero emission vehicles, several European nations are developing policy measures as part of their government programs to incentivize the timely deployment of charging infrastructure. These infrastructure policies and programs are summarized in Table 20 (Xie & Rodríguez, 2021). France, Germany, Poland, and Spain all provide infrastructure incentives for zero emission HDVs, whereas Italy, the Netherlands, and the United Kingdom don't offer any incentives. It is important to mention that in the case of Germany, the incentives are only offered for public chargers or chargers that are directly associated to certain trucks. In this case, German infrastructure incentives will not apply to the DC fast charging stations. We assume that the currently applied infrastructure incentives stay in place for the entire 2020–2030 time frame, though one could expect a gradual decrease in these premiums until they are entirely phased out.

Table 20. Summary of infrastructure incentives in the countries studied

Country	Incentive
Germany	80% of the expenditures for public chargers
Spain	40% of the total chargers' costs up to €100,000
France	€960,000 for public and private chargers
Italy	None
Netherlands	None
Poland	50% of the total cost of construction up to $40,200
United Kingdom	None

We recall the assumption that the overnight charging station supplies 80% of the truck's daily energy needs, while the DC fast charging station supplies the remaining 20%. Based on this assumption, we assume that 80% of the infrastructure incentives will be dedicated to the overnight charging station and the rest to the DC fast charging station. Infrastructure incentives will impact the electricity overhead charges in the considered countries and thus reduce the total energy costs of the BETs. Figure 11 shows the electricity overhead charges in each country after applying the country-specific infrastructure incentives. The average overhead charges curve is derived based on the average infrastructure incentives in the four countries that do provide such incentives. This is intended to be used as possible infrastructure incentives for countries that do not realize any incentives so far, including Italy, the Netherlands, and the United Kingdom. The figure shows the overhead charges between 2021 and 2030, excluding the 2020 numbers for figure scale issues. BETs operating in France benefit the most reduction in overhead charges thanks to the very generous infrastructure incentives offered in France, followed by Germany. Poland and Spain offer low incentives. For the United Kingdom, the Netherlands, and Italy, average overhead charges are considered, which represent the average infrastructure incentives of France, Germany, Poland, and Spain.

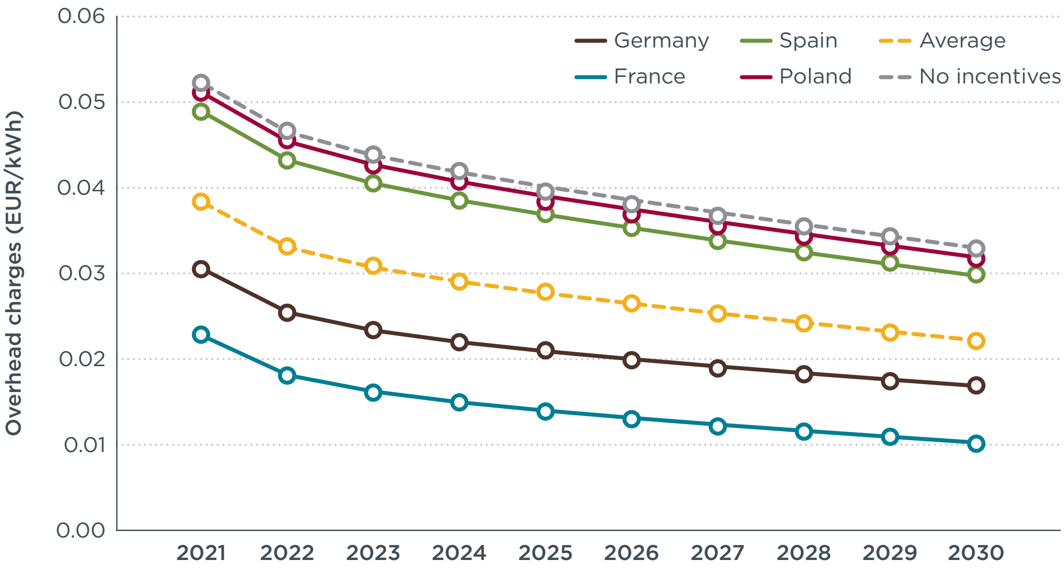

Figure 11. Electricity overhead charges with and without infrastructure incentives

Table 21 shows the impact of infrastructure incentives on the TCO parity year between BETs and diesel trucks. These incentives do not seem to have a significant impact on the TCO parity year in the countries of interest. This is mainly driven by the low share of overhead charges out of the total electricity prices, especially after 2021–2022 when the utilization ratios of charging stations increase. Although some countries do offer very generous infrastructure incentives, the share of overhead charges in the TCO of BETs is not significant enough to push the TCO parity year. Such incentives would still be very important for charging stations operators to justify their commercial viability.

Table 21. The impact of infrastructure incentives on the year TCO parity is achieved between BETs and diesel trucks

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity infrastructure incentives	2025	2029	2028	2024	2027	2027	2025

Currently adopted policy measures

This section examines the actual TCO of BETs that operate today in the studied countries, considering the currently adopted policy measures. Out of the presented policy measures, only the following currently applies:

- Purchase premiums: applies for all countries
- Infrastructure incentives: applies for Germany, France, Spain, and Poland
- Exemption or reduction in road tolls: applies for Germany
- ETS for transport: applies for Germany

Table 22 shows the BETs and diesel trucks TCO parity year under the currently adopted policy measures. BETs operating in Germany, France, and the Netherlands achieve immediate TCO parity with their diesel counterparts in 2021–2022. In the case of Germany, initially TCO parity is achieved in 2029 without any policy measures. However, the current generous purchase premiums offered in Germany, accompanied by the exemption of BETs from road tolls and the implementation of the ETS for transport, all make BETs operating in Germany the earliest to reach TCO parity among all other countries. BETs operating in other countries still manage to reach TCO parity by mid-decade.

Table 22. BETs and diesel trucks TCO parity year under the currently adopted policies

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity without incentives	2025	2029	2028	2024	2027	2027	2026
TCO parity with adopted policies	2022	2021	2027	2022	2025	2026	2026

COUNTRY-SPECIFIC ANALYSIS

In this section, country-specific analysis is conducted for each of the seven countries considered in this study. Figure 12 shows the TCO parity year for each country for different policy intervention scenarios.

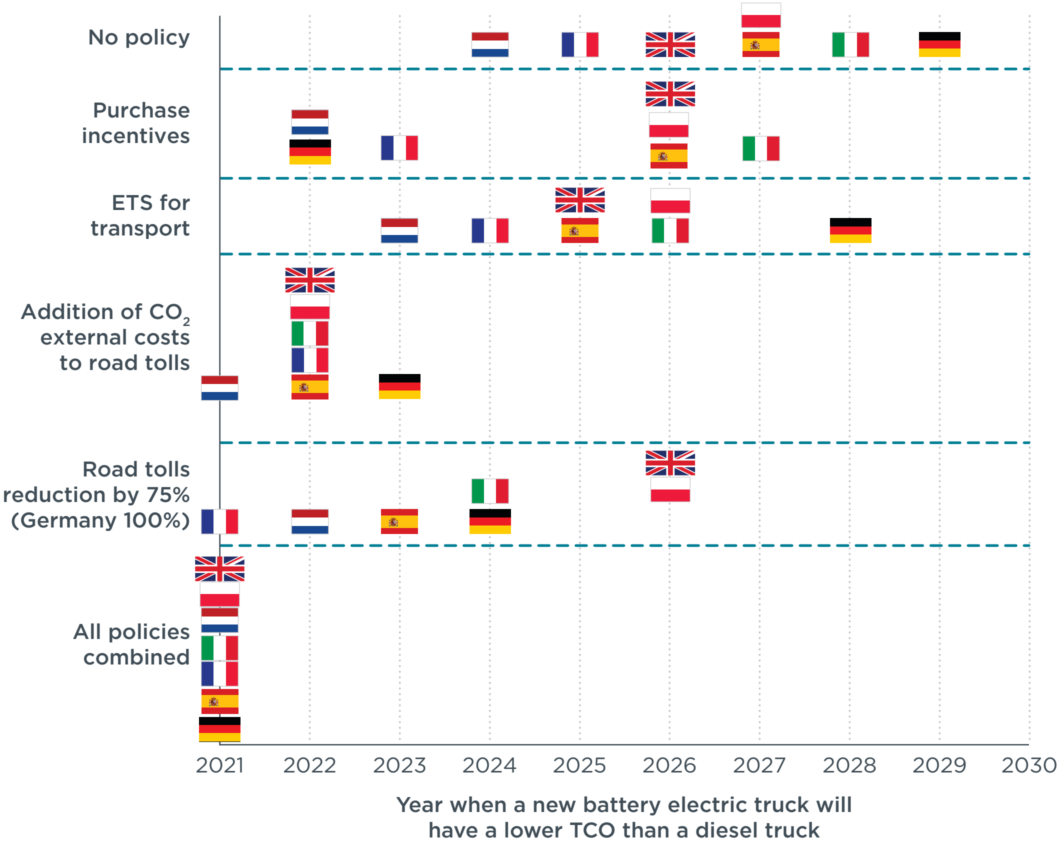

Figure 12. Summary of TCO parity time for BETs in several EU countries and under different policy intervention scenarios from the first-ownership perspective

In addition, Figure 13 shows the TCO breakdown for both BETs and diesel trucks for the following cases of interest:

1. Truck model year 2021.
2. Truck model year when TCO parity is achieved without any policy intervention.
3. Truck model year when TCO parity is achieved under a policy package that combines all measures.
4. Truck model year when TCO parity is achieved under currently adopted policy interventions.

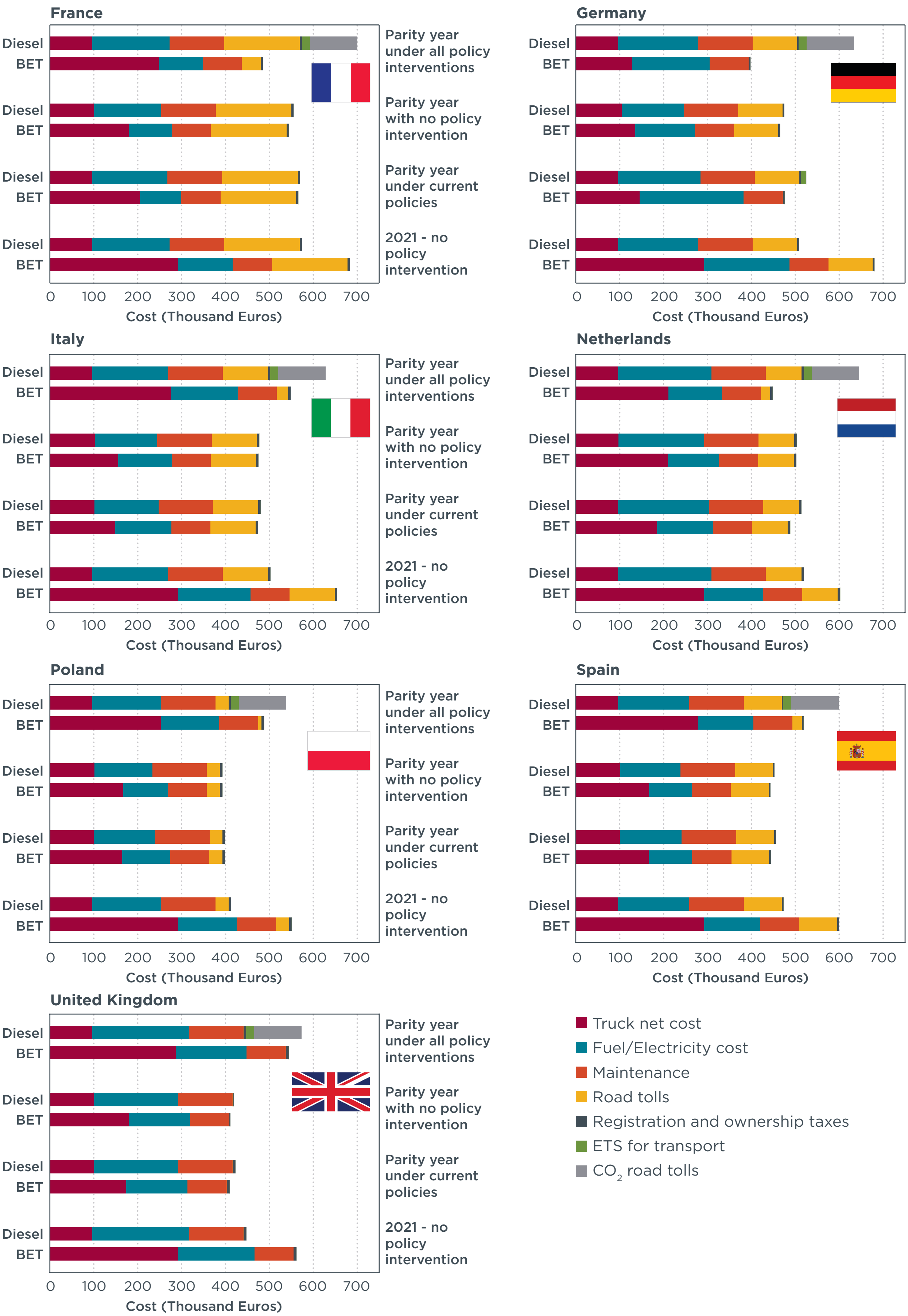

Figure 13. Country-specific TCO breakdown under the following cases: (1) truck model year 2021 with no policy intervention, (2) truck model year when TCO parity is achieved under current policy intervention, (3) truck model year when TCO parity is achieved with no policy intervention, and (4) truck model year when TCO parity is achieved with the full policy package applied

Without implementing any policy intervention, TCO parity time for BETs relative to their diesel counterparts varies significantly among the different countries considered in this study. BETs operating in the Netherlands achieve the earliest TCO parity time by 2024 because the electricity costs in the Netherlands are among the lowest in the EU, while the diesel fuel prices are the highest among all countries considered in this study. This is reflected in the high fuel cost difference between BETs and diesel trucks in the Netherlands, as shown in Figure 13. Similarly, electricity prices in France are among the lowest, helping BETs achieving an early TCO parity time with diesel trucks. On the contrary, Germany, Italy, and Poland witness the most delayed TCO parity time for BETs, achieving it only in the second half of the decade. The very high electricity costs in Germany, driven by the high imposed charges and levies, delay the TCO parity time despite a significant reduction in the BET TCO gap relative to diesel trucks during the first half of the decade. As for Italy, the high electricity costs also delay the TCO parity time of BETs, but in this case, they are mainly driven by high electric energy and supply costs. The delayed TCO parity time of BETs operating in Poland is mainly related to the low diesel prices in Poland, the lowest among all considered EU countries in this study, which makes it difficult for BETs to become cost competitive with their diesel counterparts.

As discussed earlier, policy measures in favor of electric trucks help BETs achieve TCO parity earlier. As presented earlier in Figure 12, exempting BETs from road tolls and implementing a CO_2 charge in the road toll of at least 8 EUR cents/km seem to be the most effective policy interventions as they reduce the TCO parity time by 3–4 years across all countries considered in this study. Offering purchase premiums also results in a 1- to 2-year reduction in TCO parity time, depending on the premiums amount offered in each country, except for Germany, where we witness a 7-year reduction thanks to the very generous purchase premiums offered there. A policy package combining several demand policy interventions results in an immediate TCO parity time for BETs across all countries considered in this study.

SENSITIVITY ANALYSIS

COST IMPACT OF CHARGING IN 350-KW STATIONS

One underlying assumption in this study is that a battery is sized to meet only 500 km out of the 660 km daily driving range, while the use of a 350-kW charger on the route would provide the energy needs for a truck remaining within the daily range. In this section, we examine a case where the truck battery is sized to meet the entire 660 km daily driving range without using a 350-kW fast charging station.

Table 23 shows the required truck battery size with and without the use of a 350-kW charger. The battery size is significantly increased, reaching 1,235 kWh for model years 2020, a 30% increase from the 930-kWh battery required if the 350-kW charger is used. For 2030 model years, the battery size should also increase from 675 kWh to 900 kWh. This results in a significant increase in the vehicle retail price. In addition, with the increase in battery size and weight, the BET energy consumption would increase, which is also reported in Table 23. On the other hand, charging the truck solely at 100-kW depot overnight charging stations without using the 350-kW charger reduces the charging prices; mainly the overheads are reduced because of the expensive fast charger acquisition and installation costs. It is important to mention that the impact of using the 350-kW charger on electricity costs is not fully captured as we assume flat rates per kWh for electricity transmission and distribution costs. In fact, these costs, sometimes referred to as demand charges, are highly sensitive to the charging station power demand. Because of lack of data and the complexity of the EU electricity market, this issue was ignored.

Table 23. Truck battery size requirements and energy consumption with and without the use of the DCFC 350 kW

Parameter	Model year	With DCFC	Without DCFC
Battery size	2020	930 kWh	**1,235 kWh**
	2030	675 kWh	**900 kWh**
Energy consumption	2020	1.38 kWh/km	**1.4 kWh/km**
	2030	0.99 kWh/km	**1.05 kWh/km**

Table 24 shows the BET TCO parity year with and without the use of the 350-kW charger. In most of the countries considered in this study, BET TCO parity time witnesses a 2- to 3-year delay when the 350-kW charger is not used.

Table 24. BET TCO parity year with and without the use of the DCFC 350 kW

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity with DC fast charging	2025	2029	2028	2024	2027	2027	2026
TCO parity without DC fast charging	2028	> 2030	2030	2026	2029	2029	2028

To explain this behavior, Figure 14 shows the truck net and fuel costs for model years 2021 and 2030 with and without the use of the 350-kW charger. For brevity, the figure only presents the case of Germany and the Netherlands, as these are the countries with the earliest and latest BET TCO parity time. For model years 2021, the use of the 350-kW charger will result in a lower TCO over a 5-year analysis period, driven by the significant vehicle retail price increase for larger battery sizes. In addition, although the electricity prices are reduced due to reduction in overhead charges related to the DC fast charging (DCFC) installation and acquisition costs, the increase in energy consumption balances the reduction in electricity prices, making both scenarios comparable in terms of total electricity costs. For truck model year 2030, the TCO in both cases is comparable, with a slight advantage for the case of using the DCFC station.

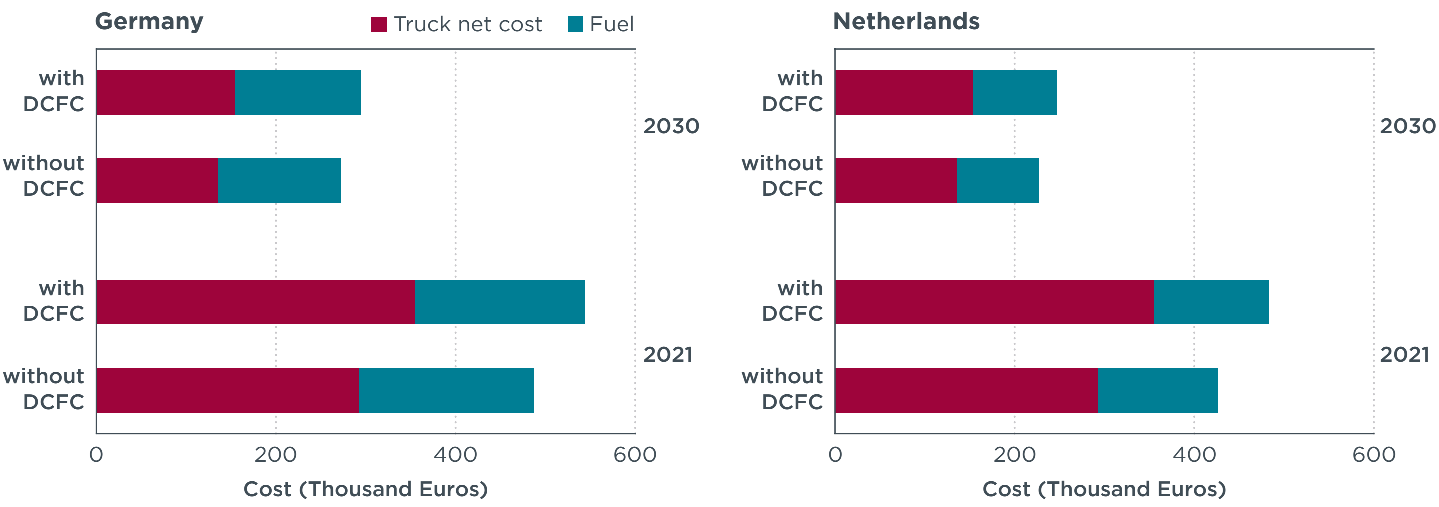

Figure 14. Truck net cost and fuel cost for model years 2021 and 2030 in Germany and Netherlands: impact of DCFC 350 kW

IMPACT OF DAILY DRIVING RANGE AND ANNUAL MILEAGE

One underlying assumption in this study is to size the battery to meet a 500-km daily driving range, with an additional 160 km worth of energy to be charged at the DCFC station, resulting in a 660 km total daily driving range per truck. Trucks operating within the borders of small countries, such as the Netherlands, might not witness such a high daily driving range. For this reason, this section analyzes the impact of reducing the daily truck driving range on the TCO parity time between BETs and diesel trucks. In addition to the 660 km daily driving range baseline scenario, two additional scenarios are explored: 560 km and 460 km daily driving ranges where the DCFC station would still provide 160 km worth of energy along the truck route. Thus, the battery is sized to provide 400 km and 300 km driving range for scenarios 1 and 2, respectively. This will result in a reduced battery size and reduced truck energy consumption, as shown in Table 25. In addition, we assume that the annual VKT will also decrease in line with the daily driving range reduction. A 15% reduction in annual VKT is considered in scenario 1 and 30% for scenario 2, in line with the daily driving range reduction for both cases.

Table 25. Truck battery size requirements and energy consumption under different daily driving range scenarios

Parameter	Model year	Baseline scenario (660 km)	Scenario 1 (560 km)	Scenario 2 (460 km)
Battery size	2020	930 kWh	**740 kWh**	**550 kWh**
	2030	675 kWh	**550 kWh**	**410 kWh**
Energy consumption	**2020**	1.38 kWh/km	**1.37 kWh/km**	**1.365 kWh/km**
	2030	0.99 kWh/km	**0.985 kWh/km**	**0.98 kWh/km**

Table 26 shows the BET TCO parity year under the three considered daily driving range scenarios. In general, the impact is not very significant on the TCO parity year, as BETs operating in most countries will achieve TCO parity a year earlier under scenario 2.

Table 26. BET TCO parity year under different daily driving range scenarios

Country	France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
TCO parity baseline (660 km)	2025	2029	2028	2024	2027	2027	2026
TCO parity scenario 1 (560 km)	2025	2029	2028	2024	2027	2026	2026
TCO parity scenario 2 (460 km)	2025	2028	2027	2023	2026	2025	2025

To better illustrate this behavior, Figure 15 shows the truck net cost and fuel net cost of BETs versus diesel trucks under different driving range scenarios for 2021 and 2030 model years. With lower daily driving ranges, the truck cost difference between BETs and diesel trucks decreases due to the smaller batteries required. On the other hand, with lower driving ranges, the truck annual VKT decreases the fuel cost advantage for BETs over diesel trucks, as can be seen more clearly in the Netherlands case. These two opposing behaviors result in a slight variation in the TCO parity year.

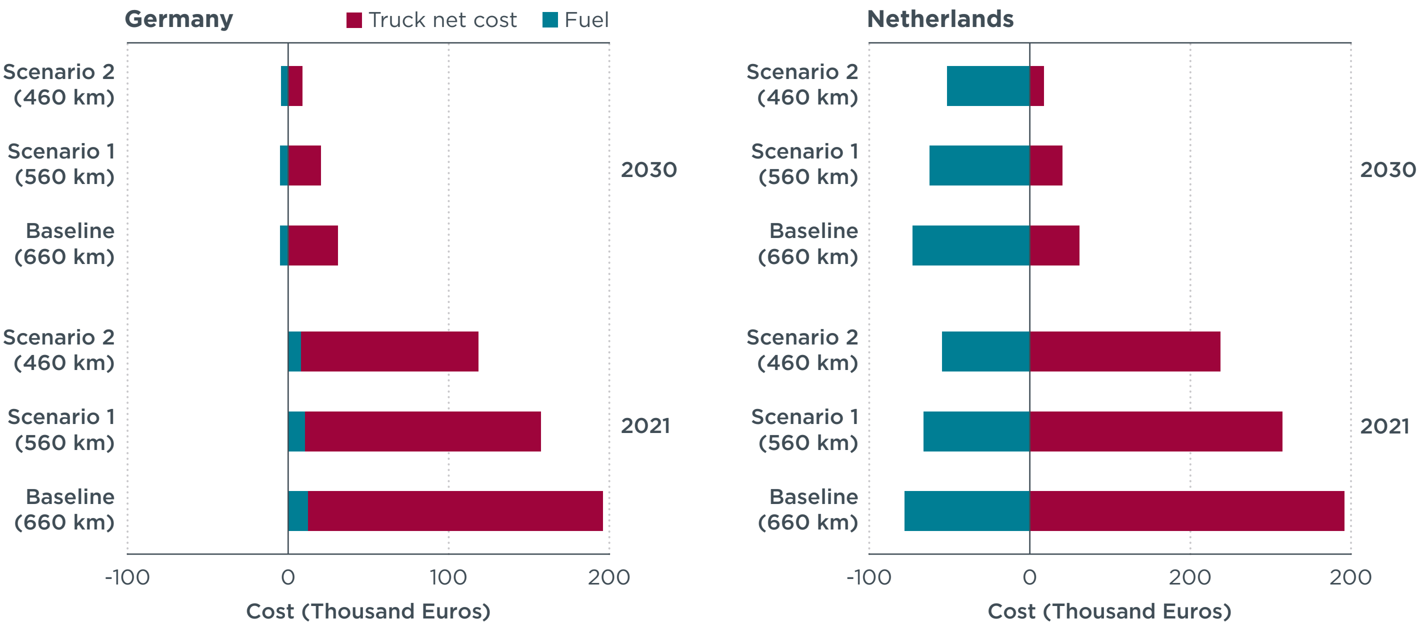

Figure 15. Truck net cost and fuel cost difference for model years 2021 and 2030 in Germany and the Netherlands: impact of daily driving range

CONCLUSIONS AND POLICY RECOMMENDATIONS

Battery-electric trucks (BETs) have gained significant momentum over the past few years, as manufacturers undergo the needed transition to achieve the European Commission's goals of carbon neutrality by 2050. However, BETs are still subject to many uncertainties regarding their total cost of ownership (TCO) and cost-effectiveness when compared to their diesel counterparts, especially in long-haul applications. This study evaluated the TCO of long-haul BETs from a first-user perspective, that is, the first 5 years of ownership, in seven European countries, including Germany, France, Spain, Italy, Poland, the Netherlands, and the United Kingdom. We arrive at the following key findings:

» **Battery electric long-haul trucks are already at TCO parity with diesel trucks in some European nations.** BETs operating in Germany, France, and the Netherlands are already at TCO parity with diesel trucks (2021–2022 TCO parity year) thanks to the currently adopted policy measures in those countries such as purchase premiums and waiving road tolls for BETs in the case of Germany.

» **Battery electric long-haul trucks will reach TCO parity during this decade in all countries considered even without any policy intervention.** The continuous improvement in battery cost and energy density will help BETs to achieve a lower TCO in comparison to diesel trucks during this decade. In addition, improvement in the truck energy efficiency reduces the energy costs and the required battery size, narrowing the TCO gap further.

» **There is a significant difference in the TCO parity time among the countries analyzed.** The different electricity and diesel prices in each country, as well as the different taxes, fees, and charges that each country imposes, especially road-use charges, result in differing TCO parity times. For example, in the absence of any active policy support, BETs operating in the Netherlands can achieve TCO parity with diesel trucks as early as 2024, while BETs operating in Germany will not achieve parity until 2029.

» **Taxes, levies, and surcharges on electricity production and transmission have a substantial impact on the TCO parity between BETs and diesel trucks.** The structure of the electricity tariffs differ among the different considered European countries. Nonrecoverable levies and surcharges, excluding VAT, substantially increase the electricity cost, such as in Germany, Italy, and the United Kingdom. This cost component in the electricity tariff structure presents challenges for BETs in achieving TCO parity with their diesel counterparts.

» **The low diesel prices in some European countries delay the year that BETs reach TCO parity with diesel trucks.** Diesel fuel prices in Poland and Spain are the lowest among the countries considered in this study. This reduces the fuel cost advantage of BETs and delays the year they reach TCO parity with diesel trucks. On the contrary, countries like the Netherlands that impose high taxes on diesel fuel prices incur the highest diesel prices, which leads to BETs achieving TCO parity with diesel trucks before mid-decade.

The study also investigated several policy interventions that could accelerate attaining TCO parity between BETs and diesel trucks. The analysis leads to the following findings and policy recommendations:

» **Implement the Eurovignette Directive into national law as soon as possible.** In-line with the agreed Eurovignette Directive, a 75% exemption is considered in this study (except for Germany where the current 100% exemption is considered). The resulting reduction in the TCO parity time is significant as BETs can reach TCO parity with diesel trucks 3 to 4 years earlier among all the considered countries, except for the United Kingdom, which doesn't impose such charges.

The agreed CO_2 charge of between 8 and 16 EUR cents/km as part of the revision to the Eurovignette Directive is an effective measure to better capture the externalities of diesel trucks, increasing their operating costs. Since BETs have no tailpipe CO_2 emissions, they are exempted from such charges. This narrows the TCO gap and leads to a TCO parity year in the first half of the decade for all countries considered.

» **Extend the European Emissions Trading Systems (ETS) to include transport.** The Fit for 55 package suggests including transport and buildings into the European ETS. Germany is the only member state considered in this study to impose carbon pricing for transport increasing from €25/tonne of CO_2 equivalent in 2021 to €55/tonne of CO_{2e} by 2025. This results in a 1-year reduction in TCO parity time between BETs and diesel trucks. To have a considerable impact on the deployment of zero-emission HDV technologies, higher carbon pricing must be imposed, and more member states are encouraged to implement similar ETS for transport.

» **Implement fiscal incentives for use of renewable electricity used for BET charging.** Taxes, levies, and surcharges contribute significantly to total electricity prices. Partially waiving the nonrecoverable electricity levies and surcharges has a substantial impact on the time TCO parity of BETs is achieved. For example, a 50% waiver on those levies and surcharges would reduce BET TCO parity time with diesel trucks by 3 years, achieving TCO parity before the middle of the decade across all countries considered. BETs operating in Germany benefit the most from this policy intervention, and their TCO parity time is reduced by 3 years. The revision of the Energy Taxation Directive should support the business case for zero-emission trucks, in particular, by allowing member states to apply tax discounts for the renewable electricity used for charging trucks.

» **Purchase premiums for trucks should be limited to incentivize the purchase of zero-emission trucks in the near term and exclude all combustion-powered trucks.** Purchase incentives are a powerful policy tool to help close the TCO gap between diesel and BETs. Currently, the countries analyzed offer purchase premiums ranging from 7,000 EUR in the United Kingdom to 450,000 EUR in Germany. Increasing the premiums up to the German level can help BETs achieve immediate TCO parity. Given that subsidies are not fiscally sustainable in the long term, they must be limited in duration and scope.

To finance programs offering purchase incentives for ZE-HDVs in the long term, fiscally sustainable alternatives must be considered. A malus component in zero-emission HDV subsidy schemes helps manage the fiscal sustainability of long-term subsidy programs, while disincentivizing vehicles and activities that emit greenhouse gases and/or air pollutants.

Subsidies can be designed as a function of the cost difference between a zero-emission truck and an internal combustion engine equivalent, as is already done in the Netherlands, Germany, and Poland. This would entail lowering the subsidy amount as battery prices continue to reduce. Furthermore, the incentives can include provisions adding eligibility criteria such as electric range and energy consumption, which can help differentiate performance of vehicles and allocate subsidies more effectively.

REFERENCES

ACEA (European Automobile Manufacturers' Association). (2021, January 20). *Zero-emission trucks: 100-fold increase needed in EU fleet, new data shows.* Retrieved from https://www.acea.auto/press-release/zero-emission-trucks-100-fold-increase-needed-in-eu-fleet-new-data-shows/

Autostrade per l'Italia. (2020). *How the toll is calculated*. Retrieved from http://www.autostrade.it/it/il-pedaggio/come-si-calcola-il-pedaggio

BAG (Bundesamt für Güterverkehr). (2021). *Förderung von leichten und schweren Nutzfahrzeugen mit alternativen und klimaschonenden Antrieben*. Retrieved from https://www.bag.bund.de/DE/Foerderprogramme/KlimaschutzundMobilitaet/KSNI/KSNI.html

Basma, H., Beys, Y., & Rodríguez, F. (2021). *Battery electric tractor-trailers in the European Union: A vehicle technology analysis*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/eu-tractor-trailers-analysis-aug21

BDF (Bundesministerium Der Finanzen). (2021). *Kfz-Steuer-Rechner.* Government of Germany. Retrieved from https://www.bundesfinanzministerium.de/Web/DE/Service/Apps_Rechner/KfzRechner/KfzRechner.html

BMU (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit). (2021). *Brennstoffemissionshandelsgesetz.* Government of Germany. Retrieved from https://www.bmu.de/GE877

BMVI (Bundesministerium für Verkehr und Digitale Infrastruktur). (2021). *Programm zur Förderung der Sicherheit und Umvelt in Unternehmen des Güterkraftverkehrs (De-Minimis)*. Government of Germany. Retrieved from https://www.bmvi.de/SharedDocs/DE/Artikel/StV/Strassenverkehr/lkw-maut.html

BMVI (Bundesministerium für Verkehr und Digitale Infrastruktur). (2018). *Richtlinie über die Förderung von energieeffizienten und/oder CO_2-armen schweren Nutzfahrzeugen in Unternehmen des Güterkraftverkehrs*. Government of Germany. Retrieved from https://www.bmvi.de/SharedDocs/DE/Anlage/StV/lkw-maut-harmonisierung.html

Braun, M. (2016). Sieben Kandidaten ziehen Bilanz. *Trans aktuell*. Retrieved from https://www.volvotrucks.de/content/dam/volvo/volvo-trucks/markets/germany/trucks/testberichte/pdf/2016/2016-09-trans-aktuell-volvo-fh-gewinnt-fehrenkoetter-test.pdf

Burke, A., & Fulton, L. (2019). *Analysis of advanced battery-electric long haul trucks: Batteries, performance, and economics*. Retrieved from Sustainable Freight Research Center, University of California, Davis https://sfreight.ucdavis.edu/publications

Burke, A., & Sinha, A. K. (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 and Institute of Transportation Studies, University of California, Davis. https://doi.org/10.7922/G2H993FJ

Buysse, C., Miller, J., Díaz, S., Sen, A., & Braun, C. (2021). *The role of the European Union's vehicle CO2 standards in achieving the European Green Deal.* Retrieved from the International Council on Clean Transportation https://theicct.org/publications/eu-vehicle-standards-green-deal-mar21

CARB (California Air Resources Board). (2019). *Proposed advanced clean trucks regulation*. Retrieved from https://ww2.arb.ca.gov/rulemaking/2019/advancedcleantrucks

Delgado, O., & Rodríguez, F. (2018). *CO2 emissions and fuel consumption standards for heavy-duty vehicles in the European Union*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/co2-emissions-and-fuel-consumption-standards-heavy-duty-vehicles-european-union

Delgado, O., Rodríguez, F., & Muncrief, R. (2017). *Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020–2030 timeframe*. Retrieved from the International Council on Clean Transportation http://www.theicct.org/EU-HDV-fuel-efficiency-tech-2020-2030

Deloitte. (2020). *Price forecast: Oil, gas & chemicals* (p. 26). Retrieved from https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/REA/ca-en-e&r-oil-gas-price-forecast-Q4-Dec2020-aoda.pdf

Department for Transport. (2018). *HGV Levy bands and rates tables*. Government of the United Kingdom. Retrieved from GOV.UK https://www.gov.uk/government/publications/hgv-levy-bands-and-rates-tables

Department for Transport. (2020). *Low-emission vehicles eligible for a plug-in grant*. Government of the United Kingdom. Retrieved from GOV.UK https://www.gov.uk/plug-in-car-van-grants

DKV. (2020). Diesel price comparison. Retrieved from https://www.dkv-euroservice.com/portal/en/web/customers/dieselpreis-index

EIA (Energy Information Administration). (2020). *Projection of crude oil prices (Brent Spot)*. Retrieved from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2020&region=0-0&cases=ref2020~highmacro~lowmacro~highprice~lowprice&start=2018&end=2050&f=A&linechart=ref2020-d112119a.3-12-AEO2020~highmacro-d112619a.3-12-AEO2020~lowmacro-d112619a.3-12-AEO2020~highprice-d112619a.3-12-AEO2020~lowprice-d112619a.3-12-AEO2020&map=&sourcekey=0

Emisia SA, Infras, & IVL. (2013). *TRACCS: Transport data collection supporting the quantitative analysis of measures relating to transport and climate change*. Funded by European Commission, DG CLIMA. Retrieved from TRACCS https://traccs.emisia.com/index.php

EPA (U.S. Environmental Protection Agency) & NHTSA (National Highway Traffic Safety Administration). (2016). *Final rule: Greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles–Phase 2: Regulatory impact analysis* (EPA-420-R-16-900). Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

European Commission. (2006). *Driving time and rest periods in the road transport sector* (Regulation (EC) No. 561/2006). Retrieved from Mobility and Transport https://eur-lex.europa.eu/summary/EN/legissum:c00018

European Commission. (2018). *Commission staff working document impact assessment: Accompanying the document Proposal for a Regulation of the European Parliament and of the Council setting CO_2 emission performance standards for new heavy duty vehicles* (SWD/2018/185 final-2018/0143 (COD)). Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD:2018:185:FIN

European Commission. (2019). *Communication from the Commission to the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions: The European Green Deal* (COM(2019) 640 final). Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission. (2020a). *Eurostat*. Retrieved from https://ec.europa.eu/eurostat/web/energy/data/database

European Commission. (2020b). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: Sustainable and smart mobility strategy—putting European transport on track for the future* (COM(2020) 789 final). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789

European Commission. (2021a). *Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757* (COM(2021) 551 final. 2021/0211 (COD)). Retrieved from https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf

European Commission. (2021b). *Proposal for a regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council* (COM(2021) 559). Retrieved from https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021PC0559

European Council. (2021). *Proposal for a Directive of the European Parliament and of the Council amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures. Analysis of the final compromise text with a view to agreement* (No. 9960/21; Interinstitutional File: 2017/0114(COD)). Retrieved from https://data.consilium.europa.eu/doc/document/ST-9960-2021-INIT/en/pdf

European Environment Agency. (2020, November 16). *EEA GHG data viewer.* Retrieved from https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

Eurovignette. (2020). *Tariffs in Euro*. Retrieved from https://www.eurovignettes.eu/portal/en/tariffs/tariffs?reset=true

Feng, W., & Figiliozi, M. (2012). Conventional vs electric commercial vehicle fleets: A case study of economic and technological factors affecting the competitiveness of electric commercial vehicles in the USA. *Procedia—Social and Behavioral Sciences*, *39*, 702–711. https://doi.org/10.1016/j.sbspro.2012.03.141

Frith, J. (2020). Lithium-ion batteries—Getting to $100/kWh. *BloombergNEF* talk. Retrieved from Vimeo https://vimeo.com/420741648

FuelsEurope. (2019, March). *Fuel price breakdown*. Retrieved from https://www.fuelseurope.eu/knowledge/refining-in-europe/economics-of-refining/fuel-price-breakdown/

Futuricum. (2021, February 18). *Electric FH*. Retrieved from https://www.futuricum.com/electric-fh/

Gerber Machado, P., Naoki Akiyoshi Ichige, E., Ninni Ramos, K., & Mouette, D. (2021). Natural gas vehicles in heavy-duty transportatio—A political-economic analysis for Brazil. *Case Studies on Transport Policy*, *9*(1), 22–39. https://doi.org/10.1016/j.cstp.2020.06.009

Hall, D., & Lutsey, N. (2019). *Estimating the infrastructure needs and costs for the launch of zero-emission trucks*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/zero-emission-truck-infrastructure

ICCT (International Council on Clean Transportation). (2019). *EU vehicle market statistical pocketbook*. Retrieved from https://theicct.org/series/eu-vehicle-market-statistical-pocketbook

IDAE (Instituto para la Diversificación y Ahorro de la Energia). (2020). *Moves II plan: Impulso a la movilidad sostenible*. Government of Spain. Retrieved from https://www.idae.es/ayudas-y-financiacion/para-movilidad-y-vehiculos/plan-moves-ii

ING Economic Bureau. (2019). *Electric trucks more financial attractive than diesels from 2028*. Retrieved from ING Group https://www.ing.nl/zakelijk/kennis-over-de-economie/uw-sector/transport-en-logistiek/electric-heavy-duty-trucks.html

Kleiner, F., & Friedrich, H. E. (2017, October). *Maintenance & repair cost calculation and Assessment of resale value for different alternative commercial vehicle powertrain technologies*. EVS30 Symposium, Stuttgart. Retrieved from https://elib.dlr.de/114666/

Krause, J., & Donati, A. (2018). *Heavy duty vehicle CO2 emission reduction cost curves and cost assessment: Enhancement of the DIONE model* (JRC112013). Publications Office of the European Union. https://doi.org/10.2760/555936

Lastauto Omnibus. (2017). *Lastauto omnibus: Katalog 2018*. EuroTransportMedia and Motorbuch Verlag.

Lutsey, N., & Nicholas, M. (2019). *Update on electric vehicle costs in the United States through 2030*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/update-US-2030-electric-vehicle-cost

Mantzos, L., Wiesenthal, T., Neuwahl, F., Rózsai, M., Europäische Kommission, & Gemeinsame Forschungsstelle. (2019). *The POTEnCIA Central Scenario: An EU energy outlook to 2050*. JRC Science for Policy Report, European Commission. https://doi.org/10.2760/32835

Mareev, I., Becker, J., & Sauer, D. U. (2018). Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. *Energies*, *11*(1), 55. https://doi.org/10.3390/en11010055

Meszler, D., Delgado, O., Rodriguez, F., & Muncrief, R. (2018). *EU HDVs: Cost effectiveness of fuel efficiency technologies for long-haul tractor-trailers in the 2025–2030 timeframe*. Retrieved from the International Council on Clean Transportation http://theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers

Ministère de l'Économie, des Finances et de la Relance. (2020). *Bonus a l'Acquisition de Vehicules Lourds Electriques ou Hydrogene*. Government of France. Retrieved from entreprises.gouv.fr https://www.entreprises.gouv.fr/fr/actualites/france-relance/bonus-pour-l-achat-de-vehicule-lourd-electrique-ou-hydrogene

Ministerie van Algemene Zaken. (2019, June 28). *Klimaatakkoord*. Government of the Netherlands. Retrieved from Rijksoverheid https://www.rijksoverheid.nl/documenten/rapporten/2019/06/28/klimaatakkoord

Ministerstwo Aktywów Państwowych. (2019). *Zapraszamy do konsultacji projektu sprawozdania z realizacji Krajowych ram polityki rozwoju infrastruktury paliw alternatywnych.* Government of Poland. Retrieved from gov.pl. https://www.gov.pl/web/aktywa-panstwowe/zapraszamy-do-konsultacji-projektu-sprawozdania-z-realizacji-krajowych-ram-polityki-rozwoju-infrastruktury-paliw-alternatywnych

Ministerstwo Infrastruktury. (2020). Platnosci za przejazdy drogowe. Government of Poland. Retrieved from gov.pl https://www.gov.pl/web/infrastruktura/platnosci-za-przejazdy-drogowe

Ministry of Infrastructure and Water Management. (2019). Introduction of heavy goods vehicle charge: On the road to a competitive and sustainable transport sector [Factsheet]. Government of the Netherlands.

MIT (Ministry of Infrastructures and Transport). (2019). *Piano strategico nazionale della mobilità sostenibile*. Government of Italy. Retrieved from https://www.sipotra.it/wp-content/uploads/2019/03/Piano-Strategico-Nazionale-della-Mobilit%C3%A0-Sostenibile-per-il-rinnovo-del-parco-mezzi-su-gomma-per-i-servizi-di-trasporto-pubblico-locale-e-il-miglioramento-della-q.pdf

Parliament and Council of the European Union. (2019). Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC. *Official Journal of the European Union, L 198*. Retrieved from http://data.europa.eu/eli/reg/2019/1242/oj

Phadke, A. A., Khandekar, A., Abhyankar, N., Wooley, D., & Rajagopal, D. (2021). *Why regional and long-haul trucks are primed for electrification now*. Retrieved from Lawrence Berkeley National Laboratory https://transportation.lbl.gov/publications/why-regional-and-long-haul-trucks-are.

Ragon, P.-L., & Rodríguez, F. (2021). *Estimated cost of diesel emissions control technology to meet future Euro VII standards*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/cost-diesel-emissions-control-euro-vii-apr2021

Rodríguez, F. (2017). *Certification of CO_2 emissions and fuel consumption of on-road heavy-duty vehicles in the European Union*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/certification-co2-emissions-and-fuel-consumption-road-heavy-duty-vehicles-european

Rodríguez, F. (2019). *CO_2 standards for heavy-duty vehicles in the European Union*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/co2-stds-hdv-eu-20190416

Satterfield, C., & Nigro, N. (2020). *Assessing financial barriers to the adoption of electric trucks*. Retrieved from Atlas Public Policy https://atlaspolicy.com/rand/assessing-financial-barriers-to-the-adoption-of-electric-trucks/

Schroten, A., Scholten, P., Wijngaarden, L. V., Essen, H. V., Brambilla, M., Gatto, M., Maffii, S., Trosky, F., Krämer, H., Monden, R., Bertschmann, D., Killer, M., Greinus, A., Lambla, V., El Beyrouty, K., Amaral, S., Nokes, T., & Coulon, A. (2019). *Transport taxes and charges in Europe: An overview study of economic internalisation measures applied in Europe*. Retrieved from Publications Office of the European Union http://publications.europa.eu/publication/manifestation_identifier/PUB_MI0319069ENN

Sripad, S., & Viswanathan, V. (2019). Quantifying the economic case for electric semi-trucks. *ACS Energy Letters*, *4*(1), 149–155. https://doi.org/10.1021/acsenergylett.8b02146

Toll Collect (2020). Mauttarife. Retrieved from https://www.toll-collect.de/de/toll_collect/bezahlen/maut_tarife/maut_tarife.html

Unterlohner, F. (2020a). *How to decarbonise the French freight sector by 2050?* Retrieved from Transport & Environment https://www.transportenvironment.org/sites/te/files/publications/2020_05_TE_how_to_decarbonise_the_french_freight_sector_by_2050_final.pdf

Unterlohner, F. (2020b). *How to decarbonise the UK's freight sector by 2050*. Retrieved from Transport & Environment https://www.transportenvironment.org/publications/how-decarbonise-uks-freight-sector-2050

Unterlohner, F. (2021). *How to decarbonise long-haul trucking in Germany: An analysis of available vehicle technologies and their associated costs.* Retrieved from Transport & Environment https://www.transportenvironment.org/publications/how-decarbonise-long-haul-trucking-germany

Wentzel, H. (2020, February 17). *Battery electric and plug-in hybrid vehicles*. Retrieved from International Transport Forum https://www.itf-oecd.org/sites/default/files/docs/battery-electric-plug-in_hybrid-vehicles-wentzel.pdf

Wettengel, J. (2021). *Germany's carbon pricing system for transport and buildings*. Retrieved from Clean Energy Wire https://www.cleanenergywire.org/factsheets/germanys-planned-carbon-pricing-system-transport-and-buildings

Wolff, S., Fries, M., & Lienkamp, M. (2020). Technoecological analysis of energy carriers for long-haul transportation. *Journal of Industrial Ecology*, *24*(1), 165–177. https://doi.org/10.1111/jiec.12937

Xie, Y., & Rodríguez, F. (2021). *Zero-emission integration in heavy-duty vehicle regulations: A global review and lessons for China* [Publication pending]. The International Council on Clean Transportation.