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A total cost of ownership comparison of truck decarbonization pathways in Europe

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Summary

Heavy-duty vehicles are a significant source of CO_2 emissions in Europe, primarily due to the sector's reliance on diesel vehicles and the nascency of regulatory efforts to curb emissions. Several alternative decarbonization pathways are being examined to replace widely-deployed diesel truck technology, including battery electric and hydrogen fuel-cell trucks, hydrogen internal combustion engine trucks, and conventional trucks powered by synthetic diesel (e-diesel), low-GHG biofuels like hydrotreated vegetable oil (HVO), and bio-compressed natural gas (bio-CNG). The future market development of truck technologies and fuels will mainly be dependent on their economic performance. This study assesses the total cost of ownership (TCO) for a variety of truck classes in Europe equipped with various powertrains and powered by different fuels.

Based on the key findings of this report, we expect battery electric trucks to be the most cost-effective decarbonization pathway in Europe, ensuring an economically viable transition from the current diesel truck before 2030, as highlighted in Figure ES1. Hydrogen fuel-cell trucks are expected to follow a decade later, as our analysis shows that they can reach TCO parity with diesel trucks by the mid-2030s. Conventional trucks powered by alternative fuels such as HVO, e-diesel, and bio-CNG, and hydrogen combustion trucks will struggle to match the economic performance of their zero-emission and diesel counterparts before 2040.

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Note: After interest in this paper, the Addendum was added on 12 December 2023.

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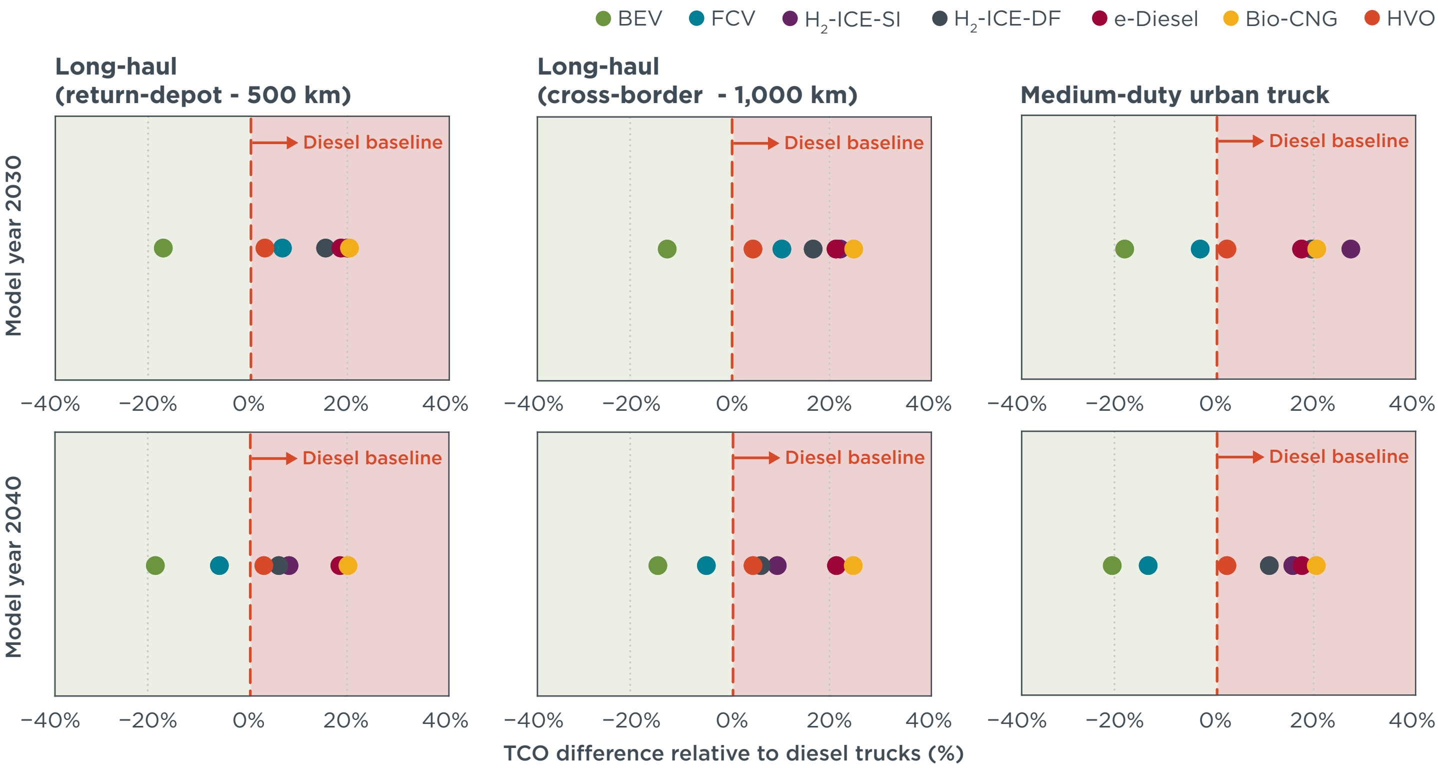

Figure ES1. TCO percentage difference relative to diesel trucks for selected truck classes in Europe in 2030 and 2040.

Introduction

Heavy-duty vehicles account for more than a quarter of greenhouse gas (GHG) emissions from road transport in the European Union (European Commission, 2023c). The HDV sector has grown reliant on diesel engine technology, partially due to the absence of regulatory efforts to curb the sector's GHG emissions. Diesel trucks accounted for more than 95% of the new HDV sales in the EU in 2021, while alternative vehicle technologies only accounted for almost 2% of new sales in the same year (Mulholland, 2022). The European Commission proposed the first EU-wide HDV CO_2 standards in 2019 (European Commission, 2019), and reviewed the standards in early 2023 (European Commission, 2023b), proposing more stringent targets given the emergence of alternative truck technologies over the past four years. While there is still some potential to improve diesel engine technology to reduce GHG emissions from the HDV sector, this potential falls short of what is needed to meet the EU's climate targets (Basma & Rodríguez, 2023).

There are several alternative truck technologies that have been examined by manufacturers to assess their technical viability for replacing the widely deployed diesel truck fleets. Battery electric and hydrogen fuel-cell trucks—referred to here as zero-emission trucks—can provide significant GHG emission reductions, especially if they are powered by renewable electricity (O'Connell et al., 2023). Another alternative truck powertrain technology that has been gaining some momentum recently is hydrogen internal combustion engine (ICE) technology. Although there are variants of this technology, it primarily relies on current compression-ignited and spark-ignited ICE technology.

The new targets proposed under the HDV CO_2 standards would mandate truck manufacturers to achieve average tailpipe emissions reductions of 43% in 2030, 64% in 2035, and 90% in 2040 for trucks. To meet those targets, the large deployment of zero-emission trucks is indispensable. Additional EU policies require a reduction of the

GHG intensity of fuels used in conventional trucks as the industry transitions towards zero-emission technologies. Despite this clear policy framework with separately regulated entities, some stakeholders are advocating for mixing these policies by allowing alternative fuels—such as synthetic diesel (e-diesel), hydrotreated vegetable oil (HVO), and bio-compressed natural gas (bio-CNG)—to count towards compliance with the HDV CO_2 standards (Baldino, et al., 2023).

Consumers in the commercial vehicle market are price sensitive, and adoption of the technologies described above is likely to be dependent on their total cost of ownership (TCO), i.e., the total costs incurred by fleets and carriers due to owning and operating a truck fleet. Building on several previous ICCT publications regarding the TCO of battery electric and hydrogen fuel-cell trucks (Basma, Saboori, et al., 2021; Basma et al., 2022), this study assesses the cost competitiveness of several alternative fuels compared to diesel and zero-emission technologies to inform the current policy debate around the HDV CO_2 standards.

Compared to previous ICCT publications assessing the TCO of trucks in the EU, this update includes:

» A summary of ICCT's TCO analysis of battery electric and hydrogen fuel-cell tractor-trailers based on Basma, Saboori, et al. (2021) and Basma et al. (2022).

» New analysis considering additional alternative technologies and fuels, including combustion engine powertrains powered by hydrogen, bio-CNG, HVO, and e-diesel.

» The extension of the analysis to cover more truck classes in the EU, including long-haul tractor-trailers, regional rigid trucks, and medium- and light-duty urban trucks.

» The extension of the analysis timeframe until 2040.

» An update of the fuel and energy costs to reflect the price fluctuations between 2020 and 2023.

This paper is split into four sections. The first section introduces the scope of the analysis, focusing on the considered truck classes and powertrain technologies. The second section focuses on the total cost of ownership methodology. In the third section, we present the TCO analysis results, and section four concludes with the main findings. The paper also includes an extensive list of appendices summarizing the main data and assumptions used to quantify the TCO.

Scope of analysis

The TCO analysis presented in this paper covers several HDV segments or VECTO groups,[1] including tractor trailers operating in long-haul with gross vehicle weight (GVW) reaching 40 tonnes, rigid trucks operating in regional delivery and urban delivery, and light-duty trucks operating in urban delivery. Table 1 summarizes the considered HDV segments in this analysis alongside select vehicle technical specifications. Data on the vehicle's annual traveled kilometers is summarized in Appendix E, Table E1.

1 The Vehicle Energy Consumption calculation Tool – VECTO is a simulation tool developed by the European Commission used for estimating the fuel consumption and CO_2 emissions of HDVs.

Table 1. Summary of considered truck segments.

Truck class	VECTO group	Axle type	Chassis type	Gross vehicle weight	2022 sales shares[a]	Power unit rating	Sizing VKT[b]
Long-haul tractor-trailer	5-LH	4x2	Tractor	> 16t	48%	350 kW	500/800/1,000 km
Regional heavy-duty truck	4-RD	4x2	Rigid	> 16t	6%	220 kW	300 km
Urban medium-duty truck	3	4x2	Rigid	12t – 16t	3%	220 kW	230 km
Urban light-duty truck	54	4x2	Rigid	5t – 7.5t	2.5%	170 kW	150 km

[a] Content supplied by IHS Markit Global S.à.r.l.;

[b] This is the vehicle daily mileage used to size its energy storage system. The operational daily VKT is different from the sizing VKT as considers the reduction in vehicle activity over its lifetime.

The HDV segments were selected to ensure comprehensive coverage of the different HDV applications in Europe, including different mission profiles, payloads, and chassis configurations while focusing on the segments with the highest sales shares. The daily driving range of long-haul tractor-trailers could vary significantly depending on the application. This would have a significant impact on the design of the truck energy storage system, and thus its retail price. We segment long-haul trucks into three subcategories based on their daily driving range:

» Long-haul trucks with a daily driving range of up to 500 km. This represents a case where the trucks return to their depots at the end of their daily operation cycle.

» Long-haul trucks with a daily driving range of up to 1,000 km. This represents a case where the trucks don't return to their depots at the end of their daily operation cycle, such as trucks that cross the borders between EU member states.

» Long-haul trucks with a daily driving range of 800 km. This represents an average use case between the two mentioned use cases.

We assess the economic viability of seven different truck decarbonization pathways: (1) battery electric, (2) hydrogen fuel cell, (3) hydrogen spark-ignited internal combustion engine, (4) hydrogen-diesel compression-ignited dual-fuel internal combustion engine, and conventional powertrains powered by (5) e-diesel, (6) HVO, and (7) bio-CNG. Figure 1 presents a schematic summarizing the different truck classes and powertrain technologies considered in this analysis.

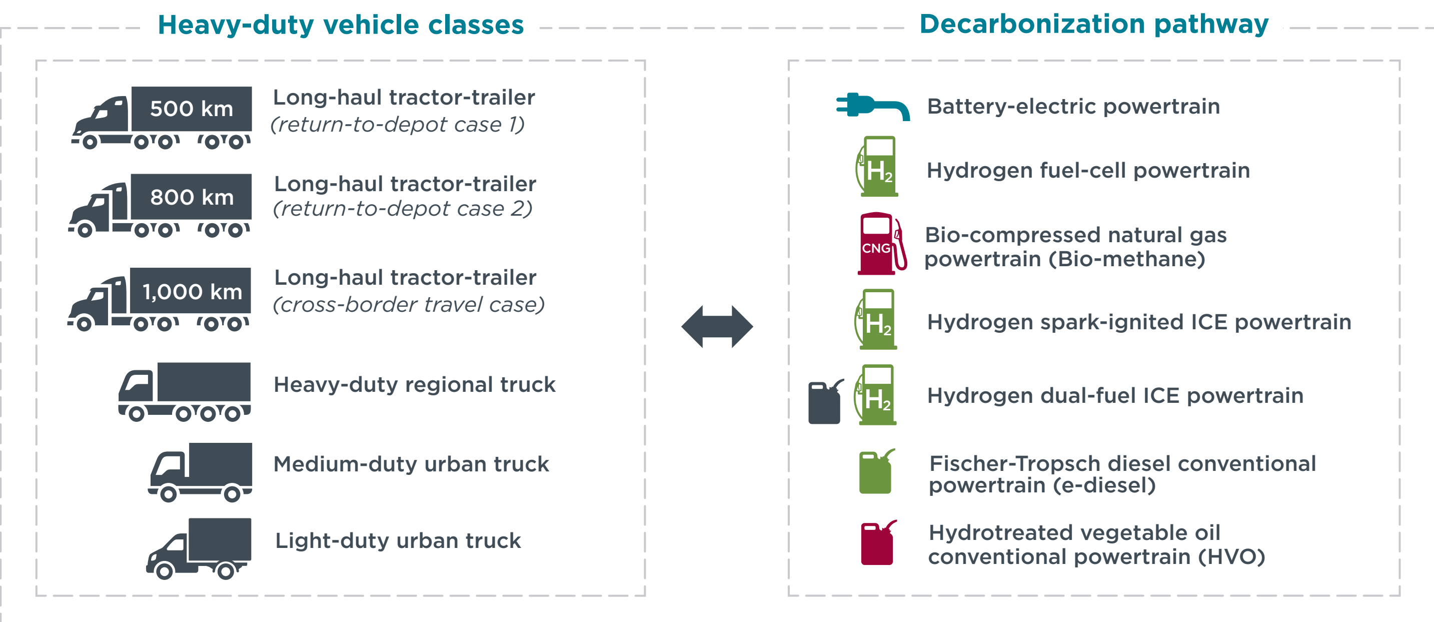

Figure 1. Schematic summarizing the scope of the analysis.

The technical specifications of the different truck classes and powertrains are developed using detailed vehicle technology analysis described in previous ICCT publications (Basma, Beys, et al., 2021; Basma & Rodríguez, 2022). More details on the fuel economy of hydrogen ICE trucks will be available in an upcoming ICCT publication. The trucks' energy and fuel consumption are estimated using multi-physical simulation models developed by ICCT with the commercial software Amesim (Simcenter, 2022). Figure 2 presents schematics for the different powertrain technologies considered in this analysis, highlighting the main components modeled in Amesim. Table A1 in Appendix A summarizes the average operational truck fuel and energy consumption for several truck classes for model years 2023 through 2040. Data on the drive cycles and payload for each truck class is summarized in Tables A1 to A4 in Basma and Rodríguez (2023).

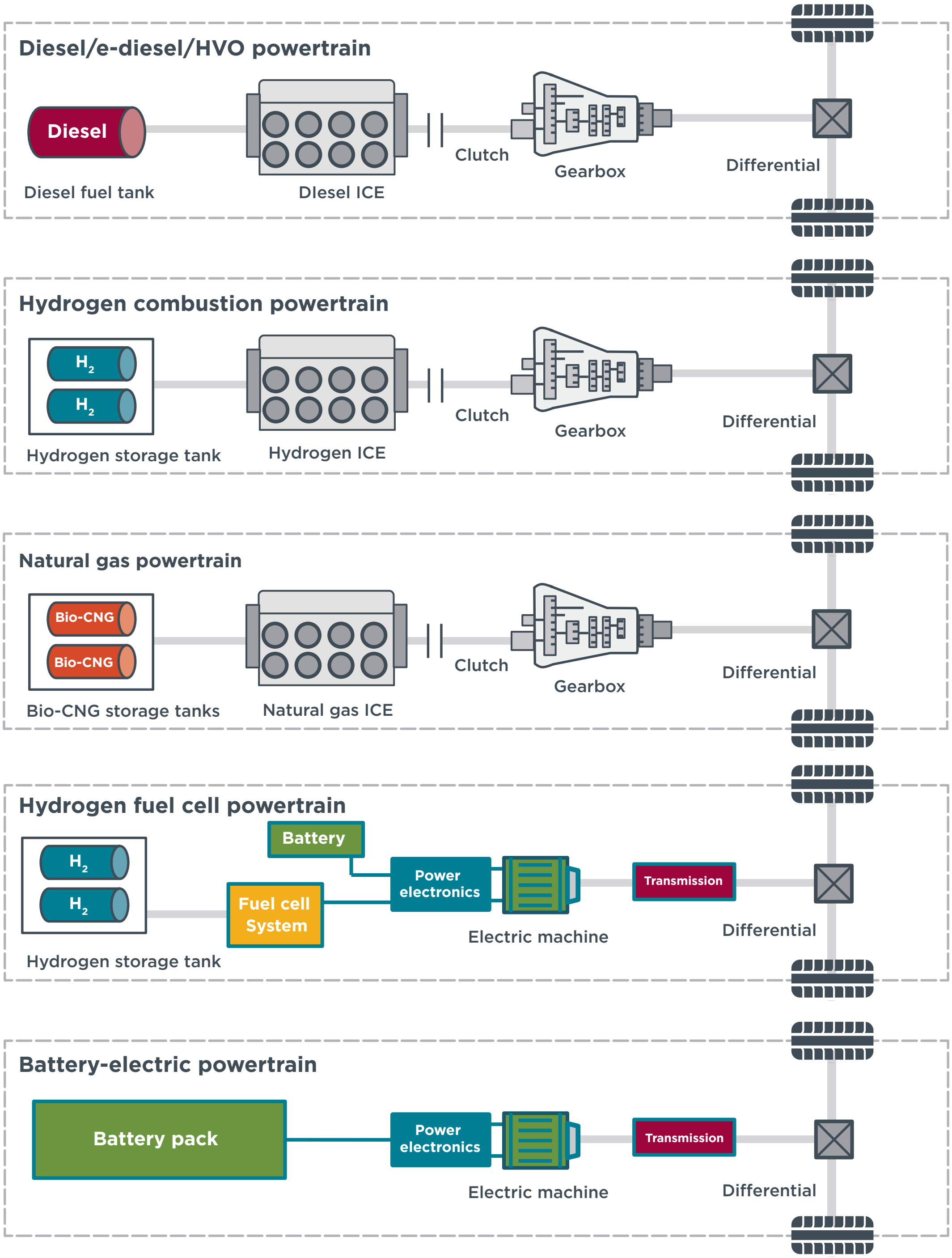

Figure 2. Schematic of the different power train configurations considered in this analysis.

Based on the truck energy consumption and the daily driving range design presented in Table 1, we estimate the required energy storage system size. Batteries for long-haul trucks are sized assuming the possibility of opportunity charging during the driver's mandatory 45-minute break. We assume 350-kW charging technology today and 1-MW charging as of 2030, when we expect MW charging to be widely deployed. For long-haul trucks driving up to 1,000 km, we assume there will be two 45-minute breaks during daily operation. The battery and hydrogen tank sizes are presented in Appendix B.

Total cost of ownership methodology

The TCO model, detailed in Basma et al. (2022) and Basma, Saboori, et al. (2021), estimates the TCO of alternative truck powertrains and fuels and compares them to a baseline diesel vehicle. The TCO is calculated by considering the trucks' fixed and operational expenses. The model then converts all fixed and operational expenses into discounted cash flows over the truck ownership period. The TCO model quantifies the truck's retail price, residual value at its end-of-life, finance costs, infrastructure costs, and all operational expenses, including fuel and energy, maintenance, labor, insurance, and taxes. The truck ownership period is assumed to be five years, and all future expenses are discounted assuming a discount rate of 9.5%, similar to what was considered in the Impact Assessment accompanying the European Commission's HDV CO_2 standards proposal (European Commission, 2023a).

Retail price and residual value

The retail prices of the conventional diesel trucks are extracted from publicly available sources. For battery electric and hydrogen fuel-cell trucks, we estimate the retail price using a bottom-up approach detailed in Xie et al. (2023). We account for the main truck and power train components such as the chassis, accessories, battery, fuel cell unit, hydrogen tanks, and electric drive. For diesel power trains, we also quantify the retail price increase due to compliance with future emissions targets. Table 2 summarizes the main alternative truck powertrain components based on a meta-study conducted by ICCT, as detailed in Sharpe and Basma (2022) and Xie et al. (2023). The meta-study is primarily based on data provided by Interact Analysis (Interact Analysis, 2022) and Ricardo Strategic Consulting (Ricardo Strategic Consulting, 2022). The truck's estimated retail prices are summarized in Table C1 in Appendix C.

Table 2. Summary of the main alternative power train components' direct manufacturing costs.

Component	2023	2030	2040
Energy battery	221 €/kWh	118 €/kWh	95 €/kWh
Power battery	392 €/kWh	232 €/kWh	186 €/kWh
Fuel cell stack	793 €/kW	289 €/kW	232 €/kW
Hydrogen tank	1,211 €/kg	810 €/kg	648 €/kg
Electric drive	58 €/kW	22 €/kW	17 €/kW
CNG tank [a]	82 €/kg	68 €/kg	62 €/kg

Note: The data reported in Xie et al. (2023) is expressed in 2022 USD. It is converted to 2023 EUR assuming an exchange rate of $1 = €0.96.

[a] Based on Hunter et al. (2021).

We also estimate the residual value of the trucks using the bottom-up approach described in Basma et al. (2023) and Mao et al. (2021). The battery, hydrogen tank, and fuel cell stack residual values are calculated depending on their lifetime and the number of charge/discharge cycles during the analysis ownership period, as highlighted in Basma et al. (2023). The trucks' residual values are summarized in Appendix D, Table D1.

Energy and fuel costs

The analysis is conducted at the European level, and all location-specific costs considered in this study are the European average. We model and collect data on the costs and retail prices of the six energy carriers considered in this analysis: (1) electrolysis hydrogen produced from renewable electricity, also known as green hydrogen, (2) diesel, (3) e-fuel, (4) electricity, (5) bio-CNG, and (6) HVO.

The retail price of **green hydrogen** is estimated considering several production pathways. In Basma et al. (2022), we quantified the cost of green hydrogen through decentralized local production. We also estimated the cost of green hydrogen imports into the EU, mainly from Brazil and Egypt, considering hydrogen production costs abroad and transportation costs to the EU.[2] In this study, we consider the lowest-cost green hydrogen production pathway, which is decentralized local production in the EU in each member state. We add the hydrogen refueling infrastructure costs to the production cost to quantify the retail price of hydrogen fuel at the pump, as detailed in Basma et al. (2022). We considered all taxes and levies on renewable electricity used to produce green hydrogen in Europe. Although it is uncertain how EU member states will assess fuel taxes and excise duties on green hydrogen, we assume the minimum level of taxation as proposed in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021), set at €0.15/GJ for renewable fuels of non-biological origins, or the equivalent of €0.018/kg. This proposal is currently in the trilogue stage of the legislative process and has not been finalized.

Diesel fuel retail price was collected from DKV Mobility (2023). We consider the three-year average net diesel fuel price in the EU-27 between 2020 and 2022, excluding VAT, as it is recoverable by fleets. The diesel price also includes excise duties and excise duty refunds, as presented in Appendix F, Table F1.

Grid electricity data was collected from Eurostat (2023a), considering the three-year average between 2020 and 2022 for commercial non-household applications. There are several rate bandwidths for commercial electricity consumers in Europe depending on the consumer's annual energy demand, and the electricity retail price varies significantly across these bandwidths. As such, different truck applications will be allocated to different commercial rate bandwidths depending on their annual energy consumption and charging location. The following summarizes the main assumptions that determine the charging cost for each truck application:

- We assume a fleet of ten trucks for all depots.
- Truck classes 54, 3, and 4-RD will rely entirely on depot charging, and are assigned rate bandwidths IB, IC, and IC, respectively, depending on the depot's annual energy demand.
- Truck classes 5-LH 500 km and 5-LH 800 km will fulfill 80% of their energy needs at depots and 20% at public charging stations. Truck class 5-LH 500 km is assigned rate bandwidth IC, and Truck class 5-LH 800 km is assigned rate bandwidth ID, depending on the depot's annual energy demand.
- Truck class 5-LH 1,000 km will rely entirely on public charging stations. A 20-MW public charging station is considered in this study in a similar approach as Basma et al. (2023). The public charging station is assigned a bandwidth IE depending on its annual energy demand.

2 An upcoming ICCT publication will provide a detailed explanation of the used methods and assumptions.

- The public station infrastructure costs include charger acquisition cost, installation, and connection to the grid due to the high-power demand of the station, which would result in expensive grid upgrades based on Basma et al., (2023). The depot infrastructure costs only include the chargers' acquisition and installation costs.
- The depots' utilization rate is assumed to be 8 hours per day, or 33%, and the public charging station utilization rate is assumed to increase linearly from 1% in 2023 to 15% in 2035, and remain constant afterward, as explained in Basma et al. (2023). We assume the infrastructure costs will be spread over the lifetime of the charging station.
- VAT on retail electricity is excluded as it is recoverable by fleets.
- Excise duties on electricity consumption are included.

As for alternative fuels, we estimate the cost of **e-diesel** produced locally in the EU and imported from Brazil and Egypt.[3] We consider two scenarios for the CO_2 source: concentrated point source (CPS) and direct air capture (DAC). DAC is a more expensive technology than capturing CO_2 from a CPS and incurs more energy-intensive processes (Zhou et al., 2022). However, due to the limited supply of CO_2 captured from CPS, DAC is expected to play an increasingly larger role in the long-term (McQuillen et al., 2022). We assume a 100% share of CPS-based e-fuel production until 2030, an equal split by 2035, and 100% DAC-based e-fuel production by 2040. For e-diesel production, we consider the cheaper option, which is importing e-diesel from Brazil to the EU. On top of the cost of e-diesel imports, we add the fuel distribution cost within the EU and the fuel handling cost at the gas station. We assume a value of €0.15/liter based on Hombach et al. (2019). We assume the minimum level of fuel taxes and excise duties, as proposed in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021), set at €0.15/GJ for renewable fuels of non-biological origins, or the equivalent of €0.0057/lde (liters diesel equivalent). This proposal is currently in the trilogue stage of the legislative process and has not been finalized.

A variety of oily feedstocks are used to produce **HVO**, including vegetable oils like palm and soy oil, which are associated with high GHG emissions and significant land use change emissions (Valin et al., 2015). The only low-GHG HVO is produced from waste oils, such as used cooking oil, which are identified in the recast of the Renewable Energy Directive (RED II)'s Annex IX, part B. HVO produced from used cooking oil and other waste oils can only play a small role in reducing GHG emissions from the EU's HDV sector, which we discuss more in the results section. We estimate the production cost in the EU to be in the range of €0.9/lde based on Pavlenko et al. (2019) and Brown et al. (2020). The values have been adjusted to 2023 euros, considering inflation. In addition, we assume a value of €0.15/liter for fuel handling and distribution costs, resulting in a total retail price of €1.16/lde. HVO production technology has reached its full maturity, and further cost and price reductions are not expected in future years. We assume the minimum level of fuel taxes and excise duties, as proposed for "sustainable biofuels" in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021), set at €5.38/GJ, or the equivalent of €0.2/lde.

In Europe, a large proportion of biogas, the precursor to biomethane, is produced from silage maize. This is not a low-GHG fuel since maize is associated with land use change emissions (Zhou et al., 2021). Here, we estimate the cost of producing **bio-CNG** in the EU from waste and residue materials, which are low-GHG but, like other biofuels, are low in availability. Based on Comer et al. (2022), the cost is around €2.03/kg, and we assume no cost reduction over time. For refueling station infrastructure costs, we adopt data from Smith and Gonzales (2014), considering a large station with a capacity of 467kg of CNG. The levelized infrastructure cost is €0.64/kg of CNG, assuming a station lifetime of 15 years. We assume the minimum level of fuel taxes and

3 An upcoming ICCT publication will provide a detailed explanation of the used methods and assumptions.

excise duties, as proposed in the Revision of the Energy Taxation Directive in Europe (European Commission, 2021), set at 0.15/GJ for advanced sustainable biofuels and biogas, or the equivalent of €0.007/kg.

Table 3 summarizes the EU-27 weighted average energy and fuel costs considered in this analysis. The weighted average cost considers the shares of freight activity in each member state, expressed in tonnes.vehicle km for each daily distance class. Each truck class is assigned a distance class based on its daily driving range. Freight activity data are extracted from Eurostat (2023b). We don't consider any fuel price subsidies in this analysis, although they may be provided in some EU Member States.

Table 3. Summary of weighted average fuel and energy retail prices in the EU-27.

	5-LH (500 km)	5-LH (800 km)	5-LH (1,000 km)	4-RD	3	54
Diesel	€1.22/liter	€1.22/liter	€1.17/liter	€1.25/liter	€1.26/liter	€1.27/liter
Charging cost	€0.21/kWh	€0.20/kWh	€0.22/kWh	€0.21/kWh	€0.21/kWh	€0.24/kWh
Green hydrogen 2023	€10.30/kg	€10.30/kg	€9.92/kg	€10.55/kg	€10.63/kg	€10.59/kg
Green hydrogen 2030	€7.77/kg	€7.77/kg	€7.42/kg	€8.00/kg	€8.06/kg	€8.07/kg
Green hydrogen 2040	€5.83/kg	€5.83/kg	€5.51/kg	€6.06/kg	€6.10/kg	€6.11/kg
E-diesel 2023	€2.51/lde					
E-diesel 2030	€2.22/lde					
E-diesel 2035	€2.24/lde					
E-diesel 2040	€2.23/lde					
Bio-CNG	€2.68/kg					
HVO	€1.36/lde					

Note: Weights are assigned based on the shares of freight activity in each member state, expressed in tonnes.vehicle km for each daily distance class.

Labor, maintenance, and insurance

Data on European-average labor costs are collected from the Comité National Routier (CNR). The data, last updated on December 2022, focuses on semi-trucks operating in long-haul and short-haul, and rigid trucks operating in short-haul (CNR, 2022). The data is presented as the driver's hourly rate for each one of the mentioned truck segments, in addition to the driver's gross salary, which includes all the employer's social security benefits. Data on travel allowances are also considered in CNR's database, which was added to the driver's basic gross salary. Similarly, we collect the annual insurance costs based on CNR data for diesel trucks, convert them into a percentage of the truck retail price, and apply them to different power train technologies with different retail prices. The labor and insurance costs data are summarized in Table 4. All vehicle technologies incur the same labor costs, and insurance costs scale to the retail price of the different vehicle technologies.

Table 4. Summary of European-average labor and insurance costs for the different truck classes considered in this study.

	5-LH (500 km)	5-LH (800 km)	5-LH (1,000 km)	4-RD	3	54
Labor (€/hour)	25.56	25.56	25.56	22.71	19.73	19.73
Annual insurance cost	2.14%	2.14%	2.14%	2.73%	2.35%	2.35%

Maintenance cost data for different truck classes and power train technologies are adopted from Basma and Rodríguez, (2023), as shown in Table 5. Assumptions regarding the maintenance costs for hydrogen ICE power trains are developed in a similar approach to Basma et al. (2023). The maintenance costs of e-diesel, HVO, and Bio-CNG power trains are assumed to be similar to those for the diesel powertrain.

Table 5. Maintenance costs by truck class and power train type in € per 100 km.

	5-LH (500 km)	5-LH (800 km)	5-LH (1,000 km)	4-RD	3	54
Diesel, e-diesel, HVO, and Bio-CNG	18.5	18.5	18.5	15.77	15.77	11
Battery electric	13.24	13.24	13.24	10.51	10.51	7.5
Hydrogen ICE 2023	19.61	19.61	19.61	16.72	16.72	11.66
Hydrogen ICE 2030 and beyond	19.15	19.15	19.15	16.32	16.32	11.36
Hydrogen fuel cell 2023	18.5	18.5	18.5	15.77	15.77	11
Hydrogen fuel cell 2030 and beyond	13.78	13.78	13.78	11.05	11.05	7.89

Road tolls and CO_2 charges

Several EU member states impose charges on road use, which are usually determined by the vehicle GVW, axle configuration, and emissions class. In general, these road charges are either distance-based or time-based. The recent reform of the Eurovignette Directive proposes replacing time-based charges with distance-based tolling, as tolling based on the duration of vehicle stay in a given country doesn't truly reflect road use (European Commission, 2022). The recent reform also dictates that zero-emission trucks be exempted from 50%–75% of distance-based road tolls as of 2023.

The tolling system in some EU member states consists of different rates for highways and local or regional roads. We assume the following shares of VKT on each type of road for the different truck classes:

» Class 54: 100% local

» Class 3: 80% local, 20% highway

» Class 4-RD: 50% local, 50% highway

» Class 5-LH (500 km): 80% highway, 20% local

» Class 5-LH (800 km): 90% highway, 10% local

» Class 5-LH (1,000 km): 95% highway, 5% local.

Using the EU Member State road charges summarized in Table F2 in Appendix F, we estimate the weighted average toll for each truck class assessed in this study, given the freight activity data for each Member State. For zero-emission trucks, i.e., battery electric and hydrogen fuel-cell electric, we apply a 50% exemption. Table 6 summarizes European-average distance-based road charges for the different truck classes considered in the TCO calculation. We assume that trucks drive 80% of their annual VKT on roads that charge tolls.

Table 6. Summary of European-average distance-based road charges for the different truck classes considered in this study.

	54	3	4-RD	5-LH (500 km)	5-LH (8000 km)	5-LH (1,000 km)
Zero-emission trucks (50% exemption)	€0.005/km	€0.017/km	€0.047/km	€0.071/km	€0.078/km	€0.064/km
All other truck technologies	€0.010/km	€0.033/km	€0.094/km	€0.142/km	€0.156/km	€0.129/km

The Eurovignette Directive also proposes a CO_2 road charge for heavy goods vehicles to account for the external cost of CO_2 emissions. The charge is defined based on the CO_2 emission class, as highlighted in the Eurovignette Directive (European Commission, 2022). Conventional powertrains running on diesel, HVO, bio-CNG, and e-diesel are allocated to CO_2 emission class 1, while battery electric and hydrogen-powered trucks are considered zero-emission vehicles and are exempt from the charges. The Eurovignette Directive also allows Member States to apply higher external-cost charges for CO_2 emissions, limited to no more than twice the values defined in the Directive. In this study, we assume the lower values of CO_2 road assessed for Euro VI vehicles, as summarized in Table 7. We assume that those charges are applied to 80% of the truck VKT.

Table 7. Summary of CO_2 road charges for different truck classes.

	54	3	4-RD	5-LH (500 km)	5-LH (8000 km)	5-LH (1,000 km)
Diesel, HVO, bio-CNG, and e-diesel trucks	€0.04/km	€0.04/km	€0.067/km	€0.08/km	€0.08/km	€0.08/km
Zero-emission trucks	€0/km					

We do not consider the costs incurred by fleets due to the European Emission Trading System for transport, which is part of the Fit for 55 packages. It is quite unclear how member states will proceed with the Emission Trading System and CO_2 road charges, and it is highly unlikely that both will be considered due to the issue of emissions double counting.

Results and discussion

This section presents a high-level summary of the key findings of the analysis and a more detailed TCO analysis for selected truck classes and technologies.

Summary of key findings

The TCO performance of the considered truck classes and powertrain technologies is ranked in Figure 3 for model year 2030, showing the TCO of each decarbonization pathway in €/km and the percentage difference relative to the lowest-cost technology. Across all truck classes, battery electric powertrains recorded the lowest TCO. Conventional trucks powered by fossil diesel are expected to be more expensive to own and operate than battery electric trucks by 15% to 23%, depending on the truck class, but would still record a better TCO than most decarbonization pathways. The exception is medium- and light-duty urban trucks, where fuel cell trucks show a better TCO compared to diesel trucks. Conventional trucks operating on 100% HVO would record a TCO 16% to 25% higher than battery electric trucks. Hydrogen fuel-cell trucks are expected to be more cost-effective than diesel and HVO for medium- and light-duty urban trucks, but would still be 14% to 32% more expensive than battery electric trucks. Hydrogen combustion powertrains and conventional trucks powered by Bio-CNG and e-diesel record the highest TCO, at 30% to 45% higher than that of battery electric trucks.

Model year 2030

	Long-haul (return-depot - 500 km)	Long-haul (return-depot - 800 km)	Long-haul (cross-border - 1,000 km)	Heavy-duty regional truck	Medium-duty urban truck	Light-duty urban truck
Lowest TCO	BEV (€0.94/km)	BEV (€0.93/km)	BEV (€0.91/km)	BEV (€0.83/km)	BEV (€0.87/km)	BEV (€1.03/km)
	Diesel (€1.15/km, +22%)	Diesel (€1.13/km, +21%)	Diesel (€1.06/km, +15%)	Diesel (€0.98/km, +18%)	FCV (€1.03/km, +18%)	FCV (€1.18/km, +14%)
	HVO (€1.18/km, +25%)	HVO (€1.16/km, +24%)	HVO (€1.1/km, +20%)	HVO (€1.0/km, +20%)	Diesel (€1.07/km, +23%)	Diesel (€1.19/km, +15%)
	FCV (€1.22/km, +29%)	FCV (€1.24/km, +32%)	FCV (€1.16/km, +27%)	FCV (€1.06/km, +27%)	HVO (€1.09/km, +25%)	HVO (€1.2/km, +16%)
	H_2-ICE-DF (€1.32/km, +40%)	H_2-ICE-DF (€1.3/km, +40%)	H_2-ICE-DF (€1.22/km, +34%)	e-Diesel (€1.12/km, +34%)	e-Diesel (€1.25/km, +44%)	e-Diesel (€1.34/km, +29%)
	e-Diesel (€1.36/km, +44%)	e-Diesel (€1.34/km, +43%)	e-Diesel (€1.27/km, +39%)	H_2-ICE-DF (€1.14/km, +37%)	H_2-ICE-DF (€1.27/km, +46%)	H_2-ICE-DF (€1.36/km, +32%)
	H_2-ICE-SI (€1.38/km, +45%)	H_2-ICE-SI (€1.36/km, +46%)	H_2-ICE-SI (€1.28/km, +40%)	H_2-ICE-SI (€1.15/km, +38%)	Bio-CNG (€1.28/km, +48%)	Bio-CNG (€1.38/km, +33%)
Highest TCO	Bio-CNG (€1.38/km, +46%)	Bio-CNG (€1.37/km, +46%)	Bio-CNG (€1.31/km, +43%)	Bio-CNG (€1.15/km, +38%)	H_2-ICE-SI (€1.36/km, +56%)	H_2-ICE-SI (€1.42/km, +37%)

Figure 3. Ranking the TCO performance per different truck classes and powertrain technologies for the model year 2030. The figure shows the TCO of each decarbonization pathway and truck class, and the percentage difference in TCO relative to the least-cost decarbonization pathway.

For truck model year 2040, all hydrogen-powered truck technologies record a significant reduction in their TCO, as presented in Figure 4. Battery electric power trains would still be the most cost-effective technology for all truck classes. Hydrogen fuel-cell trucks are expected to record the second lowest TCO, but still be 7% to 16% more expensive than battery electric trucks. Hydrogen combustion powertrain technologies are also expected to record a better TCO than their Bio-CNG or e-diesel counterparts, mainly due to the expected reduction in green hydrogen fuel prices between 2030 and 2040. Conventional trucks operating on e-diesel and Bio-CNG are expected to record the highest TCO across all truck classes, with a TCO 31% to 49% higher than battery electric trucks.

Model year 2040

	Long-haul (return-depot - 500 km)	Long-haul (return-depot - 800 km)	Long-haul (cross-border - 1,000 km)	Heavy-duty regional truck	Medium-duty urban truck	Light-duty urban truck
Lowest TCO	BEV (€0.93/km)	BEV (€0.91/km)	BEV (€0.89/km)	BEV (€0.8/km)	BEV (€0.84/km)	BEV (€1.01/km)
	FCV (€1.08/km, +16%)	FCV (€1.06/km, +16%)	FCV (€1.0/km, +11%)	FCV (€0.92/km, +14%)	FCV (€0.92/km, +9%)	FCV (€1.09/km, +7%)
	Diesel (€1.15/km, +24%)	Diesel (€1.13/km, +23%)	Diesel (€1.06/km, +18%)	Diesel (€0.98/km, +22%)	Diesel (€1.07/km, +27%)	Diesel (€1.19/km, +17%)
	HVO (€1.18/km, +27%)	HVO (€1.16/km, +27%)	HVO (€1.1/km, +22%)	HVO (€1.0/km, +24%)	HVO (€1.09/km, +29%)	HVO (€1.2/km, +18%)
	H_2-ICE-DF (€1.22/km, +31%)	H_2-ICE-DF (€1.19/km, +30%)	H_2-ICE-DF (€1.11/km, +24%)	H_2-ICE-SI (€1.05/km, +31%)	H_2-ICE-DF (€1.18/km, +40%)	H_2-ICE-DF (€1.28/km, +26%)
	H_2-ICE-SI (€1.24/km, +33%)	H_2-ICE-SI (€1.23/km, +34%)	H_2-ICE-SI (€1.15/km, +28%)	H_2-ICE-DF (€1.06/km, +32%)	H_2-ICE-SI (€1.23/km, +46%)	H_2-ICE-SI (€1.32/km, +29%)
	e-Diesel (€1.36/km, +46%)	e-Diesel (€1.34/km, +46%)	e-Diesel (€1.27/km, +42%)	e-Diesel (€1.12/km, +39%)	e-Diesel (€1.25/km, +49%)	e-Diesel (€1.34/km, +31%)
Highest TCO	Bio-CNG (€1.38/km, +48%)	Bio-CNG (€1.36/km, +49%)	Bio-CNG (€1.31/km, +47%)	Bio-CNG (€1.15/km, +43%)	Bio-CNG (€1.28/km, +52%)	Bio-CNG (€1.38/km, +35%)

Figure 4. Ranking the TCO performance per different truck classes and powertrain technologies for the model year 2040.shows the TCO of each decarbonization pathway and truck class, and the percentage difference in TCO relative to the least-cost decarbonization pathway.

The same information is presented in Figure 5, highlighting the TCO differences for all considered decarbonization pathways relative to diesel trucks. As seen in the figure, battery electric trucks—and hydrogen fuel-cell trucks a decade later—can achieve a lower TCO relative to diesel trucks across all truck classes.

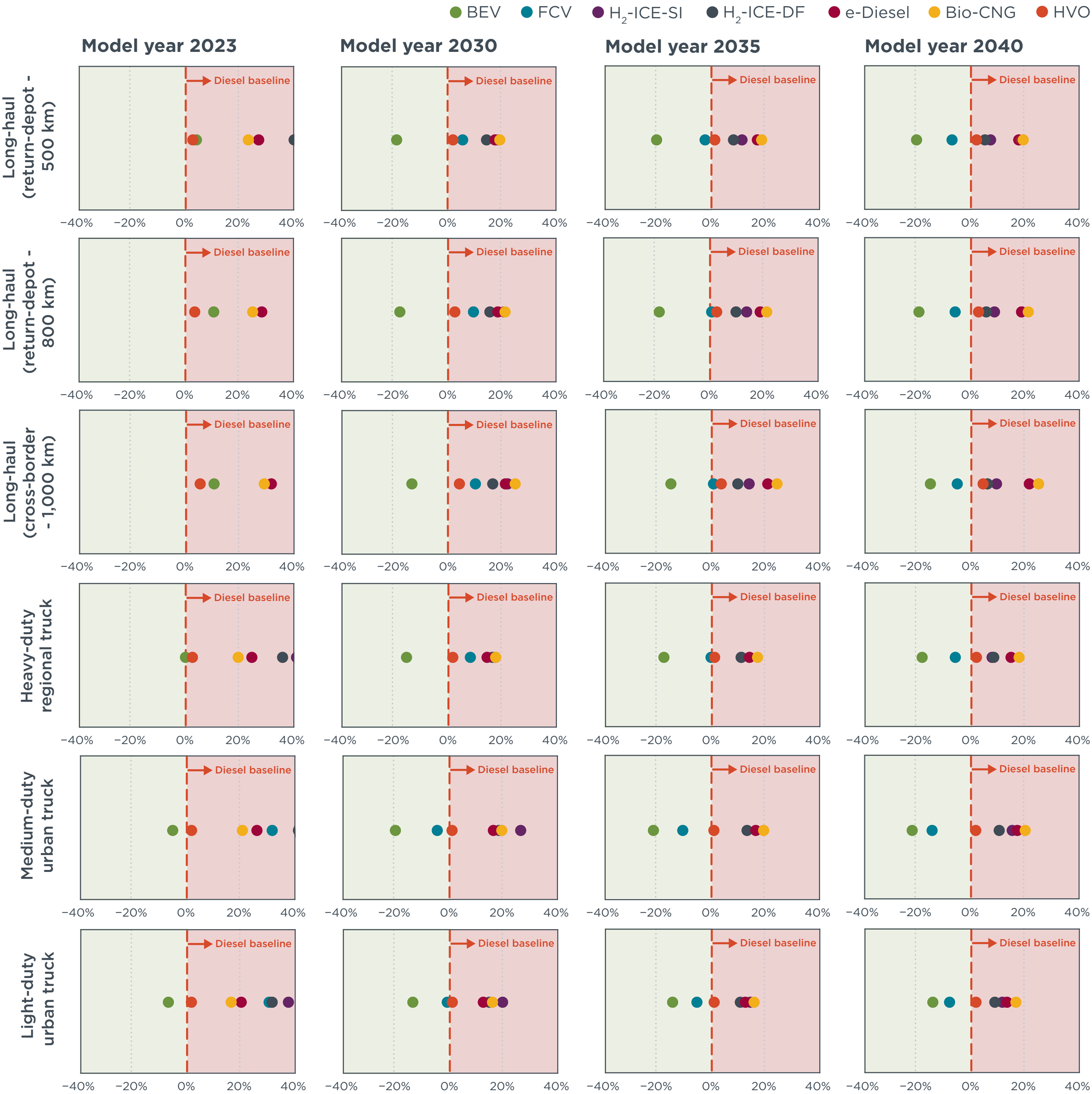

Figure 5. TCO percentage difference relative to diesel trucks.

Table 8 presents a summary of the TCO parity year for different truck classes and powertrain technologies relative to a diesel-equivalent truck. For long-haul trucks, battery electric powertrains are expected to reach TCO parity with diesel trucks between 2025 and 2026, depending on the daily mileage and battery size. Fuel cell long-haul trucks will reach TCO parity with diesel ten years later, between 2035 and 2036. All other alternative long-haul truck technologies are not projected to achieve TCO parity with diesel long-haul trucks before the end of the 2030s.

For medium- and light-duty urban trucks, battery electric powertrains are already at TCO parity with their diesel counterparts, while hydrogen fuel-cell trucks are expected to reach TCO parity by 2030. All other alternative medium- and light-duty urban truck technologies are not projected to achieve TCO parity with their diesel equivalents before 2040.

Table 8. Summary of TCO parity year relative to diesel trucks

	Long-haul return-depot (500 km)	Long-haul return-depot (800 km)	Long-haul cross-boarder (1,000 km)	Regional heavy-duty truck	Urban medium-duty truck	Urban light-duty truck
BEV	2025	2026	2026	2023	2023	2023
FCV	2035	2036	2036	2036	2030	2030
HVO	Beyond 2040 or not at all					
E-diesel						
H2-ICE-SI						
H2-ICE-DF						
Bio-CNG						

Class-specific analysis

This section presents a deeper dive at the TCO results for selected truck classes, focusing on: (1) long-haul heavy-duty trucks return-depot 500 km, (2) long-haul heavy-duty trucks cross-border 1,000 km, and (3) medium-duty urban trucks. These truck classes represent the most important in the EU in terms of market shares and GHG emissions. Detailed results for the other truck classes can be found in Appendix G.

Long-haul heavy-duty trucks return-depot 500 km

This truck class records the highest sales share and is responsible for the largest share of the EU HDV sector GHG emissions. Figure 6 presents the TCO breakdown for the long-haul truck return-depot 500 km case for different decarbonization pathways for model years 2023, 2030, 2035, and 2040. For truck model year 2023, the diesel truck is cheaper than all decarbonization pathways, recording a 5% lower TCO than battery electric trucks. This is mainly driven by the high retail price of battery electric trucks in 2023. Hydrogen fuel-cell trucks record the highest TCO due to a combination of high retail prices and high fuel expenses. Other hydrogen-powered truck technologies also record a very high TCO. Trucks operating on Bio-CNG and e-diesel are 20% and 30% more expensive than diesel trucks, respectively, while trucks running on low-GHG HVO would result in a 3% higher TCO than diesel trucks. This behavior is mainly driven by a combination of high retail fuel prices and low vehicle energy efficiency, resulting in high operational expenses.

In model year 2030, battery electric trucks become the most effective decarbonization pathway, thanks to the projected reduction in battery prices. Hydrogen fuel-cell trucks are also expected to record a significant TCO reduction, making them only 6% more expensive than their diesel equivalent. Trucks running on e-diesel are expected to record an 18% higher TCO than diesel trucks. It is worth mentioning that, although the e-diesel is expected to be ~80% more expensive than fossil diesel, the TCO difference is lower (18% in this case) when taking into account the other TCO components such as retail price, labor, and road tolls.

By 2035, hydrogen fuel-cell trucks are expected to achieve TCO parity with their diesel equivalent, while Bio-CNG and e-diesel trucks are expected to have the highest TCO.

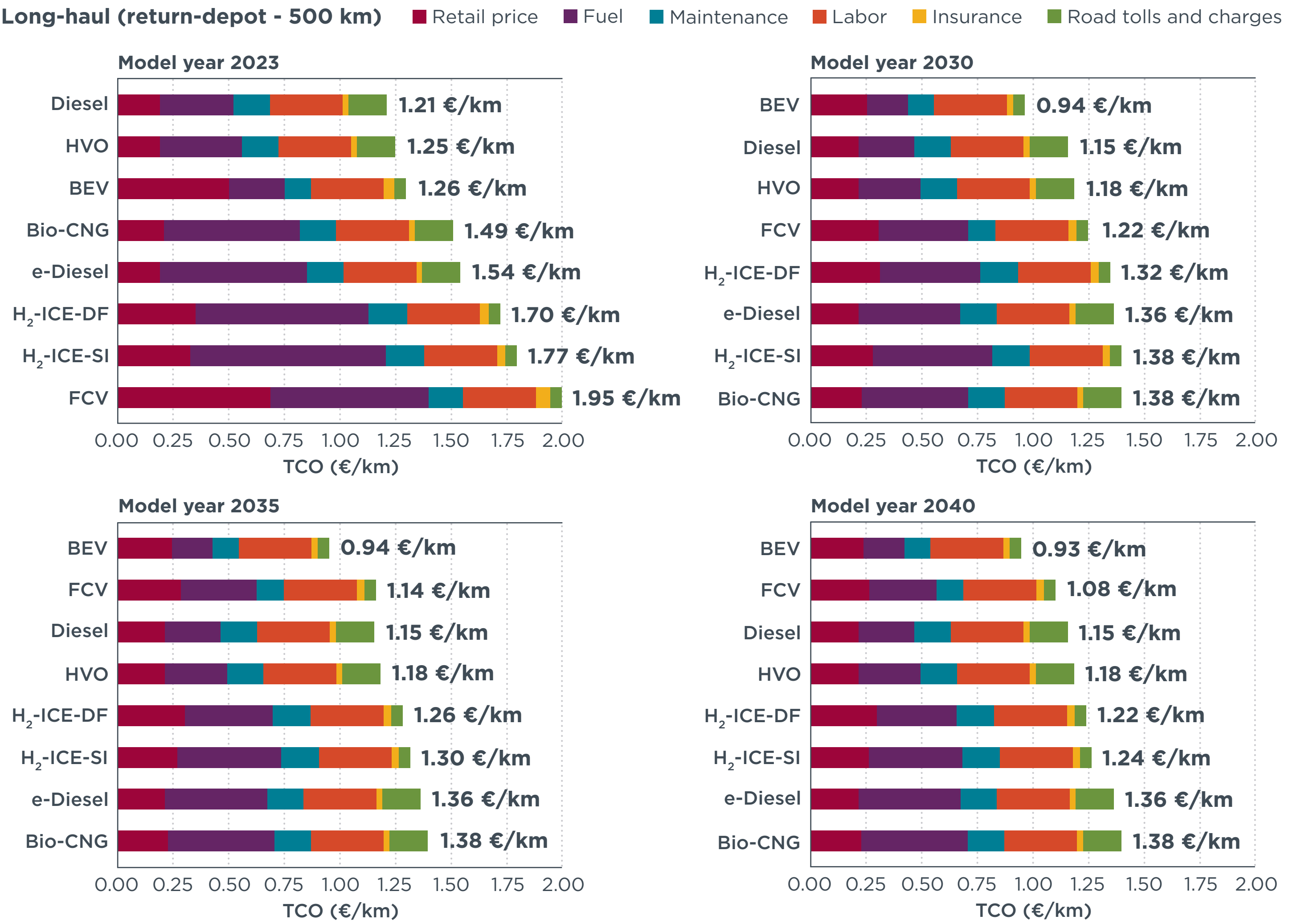

Figure 6. TCO breakdown for long-haul truck return-depot 500 km case for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

Long-haul heavy-duty trucks cross-border 1,000 km

Cross-border long-haul travel is one of the most challenging segments to decarbonize, given the very long daily driving ranges. The results presented in Figure 7 suggest that battery electric trucks can provide a cost-effective alternative to diesel trucks as early as 2030. Although battery electric trucks are almost 10% more expensive than diesel trucks in 2023, the two technologies will reach cost parity before 2030. In the long term, hydrogen fuel-cell trucks are expected to be the second-best alternative to diesel trucks, while trucks powered by e-diesel and bio-CNG will record the highest TCO due to their high fuel expenses.

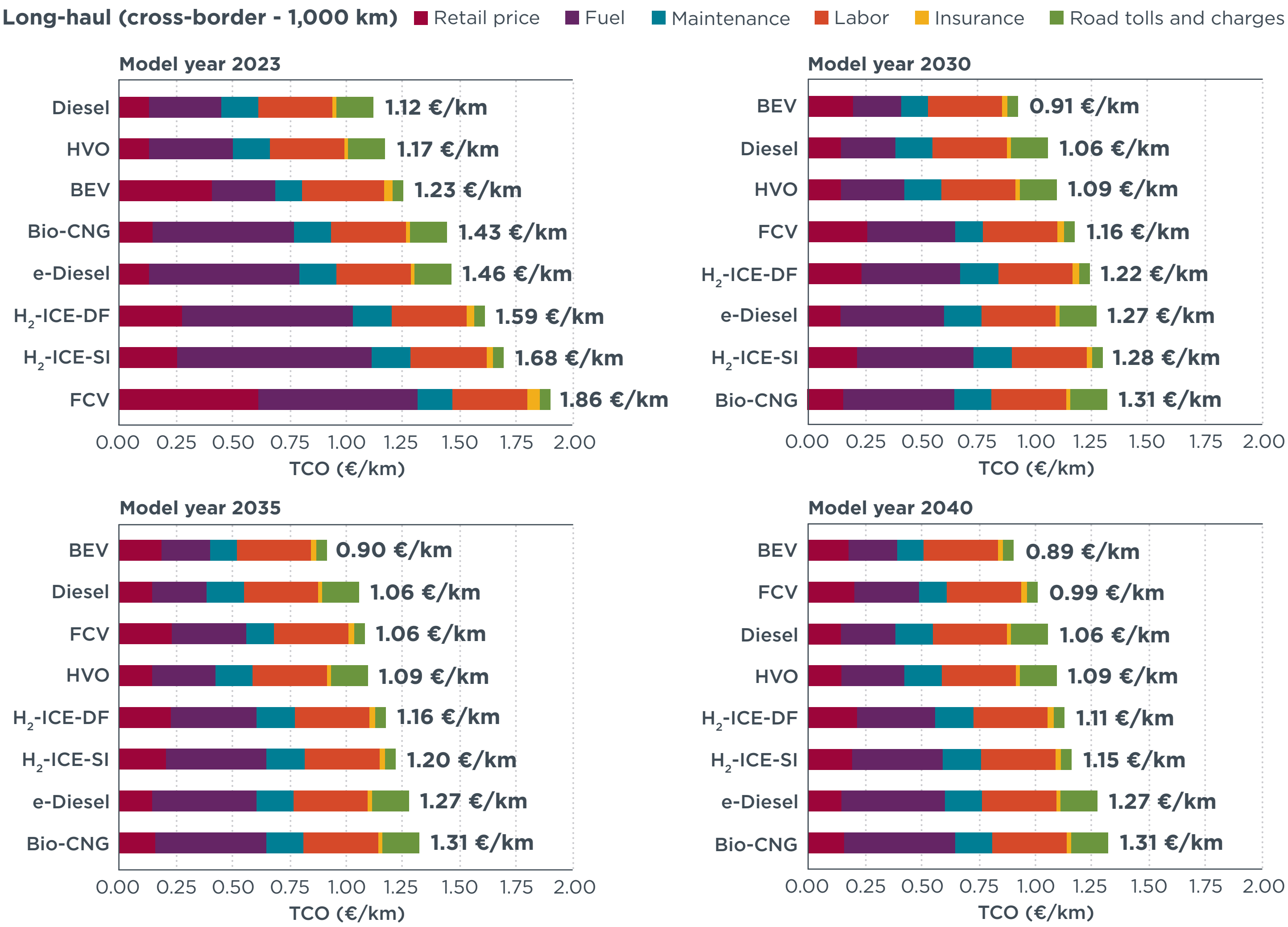

Figure 7. TCO breakdown for long-haul truck cross-border 1,000 km case for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

Medium-duty urban trucks

This truck class accounts for almost 4% of the total HDV sales, and its electrification potential is high given the low daily mileage covered during operation and relatively lower payload capacity needs relative to heavy-duty trucks. As shown in Figure 8, our TCO analysis suggests that battery electric trucks are already more cost-effective than diesel trucks, while hydrogen fuel-cell trucks will reach TCO parity with diesel as early as 2030. Similar to the findings for the other truck classes, e-diesel and bio-CNG are the most expensive decarbonization pathways for medium-duty urban trucks.

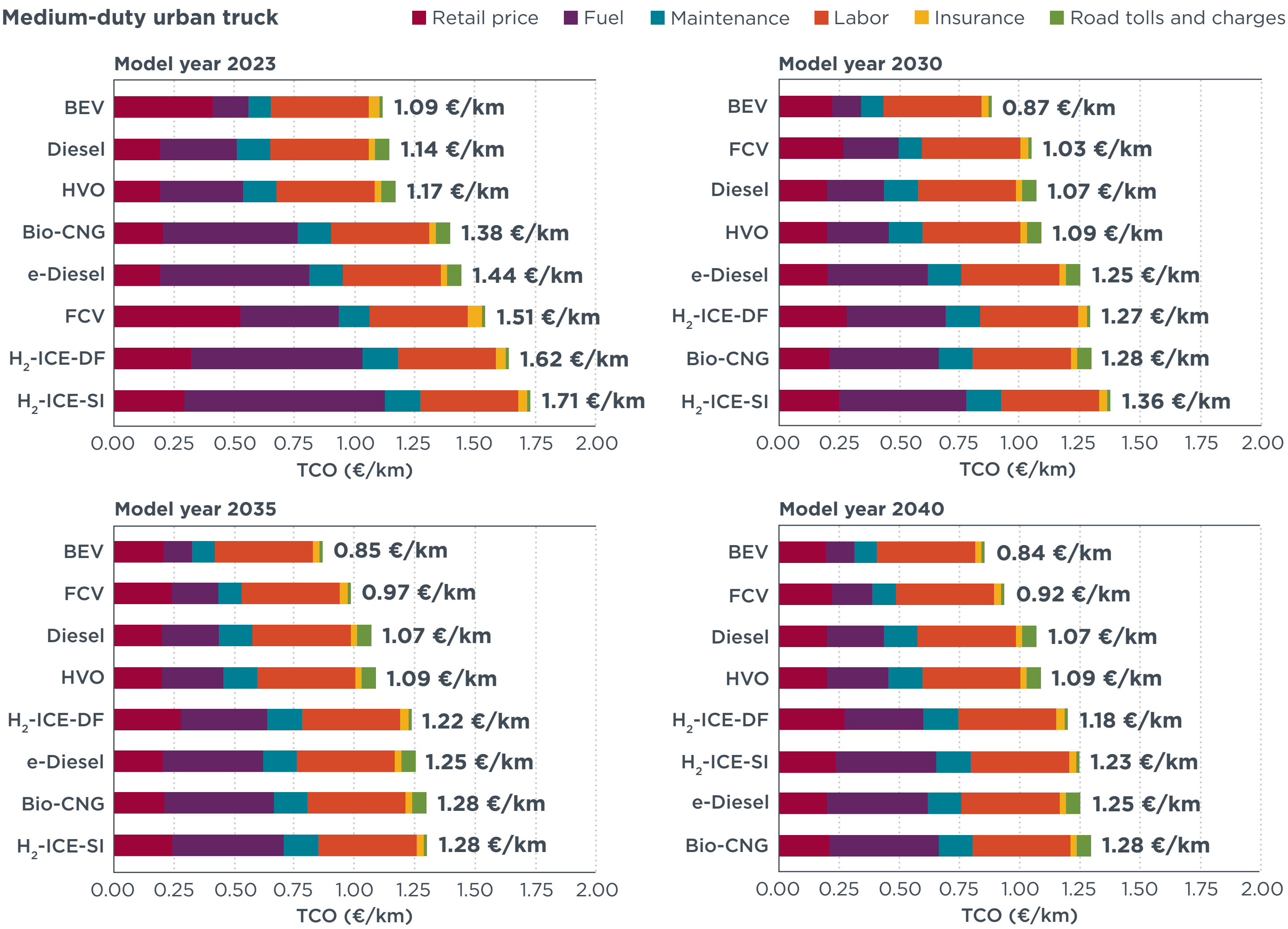

Figure 8. TCO breakdown for medium-duty urban trucks for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

Conclusions

This study presents a comprehensive TCO analysis for various truck classes equipped with different powertrain technologies and powered by different fuels in Europe. The analysis covers truck classes that represent the diverse range of truck applications in Europe, focusing on trucks with different mission profiles, payloads, driving ranges, and chassis configurations. The analysis examines eight different powertrain technologies and fuels: diesel, battery electric, hydrogen fuel-cell, hydrogen ICE, hydrogen-diesel dual fuel ICE, and conventional trucks operating on e-diesel, bio-CNG, and HVO from low GHG feedstock. Our key findings suggest the following:

» **Battery electric powertrains are expected to be the most cost-effective technology for most truck classes before 2030**. For medium- and light-duty urban trucks, battery electric powertrains are already at TCO parity with their diesel counterparts. For heavy-duty long-haul trucks, battery electric powertrains will reach TCO parity with diesel between 2025 and 2026. Even for the very challenging long-haul cross-border truck applications, battery electric technology can provide the most cost-effective solution before 2030, assuming the availability of a high-power MW public charging infrastructure in Europe.

» **Hydrogen fuel-cell powertrains are expected to become cost-competitive with diesel trucks by 2035**. For medium- and light-duty urban trucks, hydrogen fuel-cell powertrains are expected to reach TCO parity with diesel trucks by 2030. However, the technology won't be able to match the economic performance of diesel trucks in the long-haul segment before 2035, given the expected cost of green hydrogen fuel in the 2030–2040 timeframe. In the long term, fuel-cell trucks will record a 10% to 20% higher TCO than battery electric trucks.

» **Conventional trucks fueled by alternative fuels such as HVO, e-diesel, and bio-CNG are not expected to reach TCO parity with diesel trucks before 2040 and will record a 15% to 45% higher TCO than their zero-emission counterparts by 2030, depending on the truck class.** Trucks operating on e-diesel or bio-CNG will struggle to match the lower TCO of zero-emission trucks and diesel trucks in the long term and are expected to record the highest TCO among all considered decarbonization pathways and across all truck classes, primarily driven by the high fuel costs and lower vehicle energy efficiency. By 2030, trucks running on 100% HVO will record a better TCO than those powered by e-diesel and bio-CNG, and hydrogen combustion trucks, but would still be 20% to 30% more expensive than battery electric trucks. Further, low-GHG HVO from waste oils is low in availability.

» **Hydrogen combustion trucks won't be able to match the economic performance of their zero-emission or diesel counterparts, but are expected to record a better TCO than conventional trucks powered by e-diesel and bio-CNG in the long term**. Driven by the price of green hydrogen fuel and the higher fuel consumption relative to zero-emission trucks, both hydrogen combustion powertrains are expected to be 25% to 45% more expensive than battery electric trucks by 2040. However, the technology's economic performance can overcome that of conventional trucks powered by e-diesel and bio-CNG, recording up to 15% lower TCO for long-haul trucks.

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Appendix A: Truck energy and fuel consumption

The data presented in Table A1 is based on vehicle technology analysis and simulation presented in Basma, Beys, et al. (2021) for battery-electric trucks, Basma and Rodríguez (2022) for hydrogen fuel-cell and diesel trucks, and in an upcoming ICCT publication for hydrogen ICE trucks.

Table A1. Summary of average operational truck fuel/energy consumption for several truck classes for MY 2023 through 2040.

Technology	Truck class	2023	2030	2040
Diesel/e-diesel/HVO (LDE/100km)	5-LH (500 km)	30.7	23.2	23.2
	5-LH (800 km)	30.7	23.2	23.2
	5-LH (1,000 km)	30.7	23.2	23.2
	4-RD	24.1	16.1	16.1
	3	28.8	21.2	21.2
	54	23.8	17.6	17.6
Battery electric (kWh/100km)	5-LH (500 km)	138	101	101
	5-LH (800 km)	141	103	103
	5-LH (1,000 km)	141	108	108
	4-RD	93	71	71
	3	81	65	65
	54	58	48	48
Hydrogen fuel-cell (kg/100km)	5-LH (500 km)	8.32	6.13	5.82
	5-LH (800 km)	8.41	6.16	5.85
	5-LH (1,000 km)	8.53	6.18	5.88
	4-RD	5.31	3.69	3.38
	3	4.62	3.37	3.11
	54	3.33	2.48	2.27
Hydrogen ICE SI (kg/100km)	5-LH (500 km)	10.28	8.13	8.13
	5-LH (800 km)	10.37	8.17	8.17
	5-LH (1,000 km)	10.42	8.18	8.18
	4-RD	7.92	5.96	5.96
	3	9.41	7.74	7.74
	54	7.81	6.41	6.41
Hydrogen ICE CI DF (kg/100km) | (l diesel/100km) [a)]	5-LH (500 km)	8.71 | 3.06	6.48 | 2.21	6.48 | 2.21
	5-LH (800 km)	8.74 | 3.07	6.51 | 2.21	6.51 | 2.21
	5-LH (1,000 km)	8.76 | 3.08	6.55 | 2.23	6.55 | 2.23
	4-RD	6.64 | 2.29	4.91 | 1.68	4.91 | 1.68
	3	7.72 | 2.68	5.67 | 1.96	5.67 | 1.96
	54	6.41 | 2.27	4.86 | 1.77	4.86 | 1.77
CNG (kg/100km)	5-LH (500 km)	25.70	20.16	20.16
	5-LH (800 km)	25.79	20.35	20.35
	5-LH (1,000 km)	26.25	20.66	20.66
	4-RD	19.64	14.84	14.84
	3	23.62	19.20	19.20
	54	19.37	16.15	16.15

a) The Hydrogen CI ICE DF fuel consumption is calculated assuming the following fuel mix between hydrogen and diesel: 90%:10%

Appendix B: Truck energy storage system sizing

Table B1. Battery-electric truck battery size in kWh for several truck classes for MY 2023 through 2040

Truck class	2023	2030	2040
5-LH (500 km)	760 kWh	405 kWh	405 kWh
5-LH (800 km)	1,000 kWh	680 kWh	680 kWh
5-LH (1,000 km)	1,000 kWh	870 kWh	870 kWh
4-RD	360 kWh	280 kWh	280 kWh
3	250 kWh	200 kWh	200 kWh
54	120 kWh	100 kWh	100 kWh

Table B2. Hydrogen-powered and Bio-CNG trucks tank size in kg of usable fuel for several truck classes for MY 2023 through 2040.

Truck class	Technology	2023	2030	2040
5-LH (500 km)	Fuel cell	45 kg	33 kg	32 kg
	SI ICE	55 kg	44 kg	44 kg
	DF ICE	47 kg	35 kg	35 kg
	Bio-CNG	139 kg	109 kg	109 kg
5-LH (800 km)	Fuel cell	73 kg	54 kg	51 kg
	SI ICE	80 kg	70 kg	70 kg
	DF ICE	76 kg	62 kg	62 kg
	Bio-CNG	180 kg	174 kg	174 kg
5-LH (1,000 km)	Fuel cell	80 kg	67 kg	64 kg
	SI ICE	80 kg	80 kg	80 kg
	DF ICE	80 kg	78 kg	77 kg
	Bio-CNG	180 kg	180 kg	180 kg
4-RD	Fuel cell	16 kg	11 kg	10 kg
	SI ICE	24 kg	18 kg	18 kg
	DF ICE	20 kg	15 kg	15 kg
	Bio-CNG	60 kg	47 kg	47 kg
3	Fuel cell	11 kg	9 kg	8 kg
	SI ICE	22 kg	18 kg	18 kg
	DF ICE	18 kg	13 kg	13 kg
	Bio-CNG	58 kg	48 kg	48 kg
54	Fuel cell	8 kg	6 kg	5 kg
	SI ICE	18 kg	15 kg	15 kg
	DF ICE	15 kg	11 kg	11 kg
	Bio-CNG	48 kg	40 kg	40 kg

Appendix C: Truck retail price

Table C1. Summary of the trucks' estimated retail prices for model years 2023, 2030, and 2040.

Truck class	Technology	2023	2030	2040
5-LH (500 km)	Diesel	€152k	€167k	€167k
	BEV	€354k	€181k	€159k
	FCV	€486k	€195k	€175k
	H2-SI-ICE	€250k	€213k	€200k
	H2-DF-ICE	€266k	€234k	€224k
	e-Diesel	€152k	€167k	€167k
	Bio-CNG	€159k	€169k	€168k
	HVO	€152k	€167k	€167k
5-LH (800 km)	Diesel	€176k	€192k	€192k
	BEV	€457k	€222k	€202k
	FCV	€675k	€226k	€203k
	H2-SI-ICE	€320k	€266k	€246k
	H2-DF-ICE	€344k	€289k	€270k
	e-Diesel	€176k	€192k	€192k
	Bio-CNG	€188k	€199k	€198k
	HVO	€176k	€192k	€192k
5-LH (1,000 km)	Diesel	€176k	€192k	€192k
	BEV	€457k	€239k	€218k
	FCV	€688k	€236k	€211k
	H2-SI-ICE	€320k	€278k	€254k
	H2-DF-ICE	€352k	€307k	€283k
	e-Diesel	€176k	€192k	€192k
	Bio-CNG	€188k	€200k	€198k
	HVO	€176k	€192k	€192k
4-RD	Diesel	€84k	€88k	€88k
	BEV	€186k	€100k	€88k
	FCV	€311k	€114k	€96k
	H2-SI-ICE	€125k	€105k	€100k
	H2-DF-ICE	€139k	€123k	€119k
	e-Diesel	€84k	€88k	€88k
	Bio-CNG	€85k	€87k	€87k
	HVO	€84k	€88k	€88k
3	Diesel	€78k	€82k	€82k
	BEV	€152k	€85k	€76k
	FCV	€194k	€104k	€88k
	H2-SI-ICE	€116k	€98k	€93k
	H2-DF-ICE	€125k	€110k	€106k
	e-Diesel	€78k	€82k	€82k
	Bio-CNG	€79k	€81k	€80k
	HVO	€78k	€82k	€82k
54	Diesel	€50k	€54k	€54k
	BEV	€94k	€60k	€55k
	FCV	€176k	€89k	€74k
	H2-SI-ICE	€81k	€69k	€64k
	H2-DF-ICE	€89k	€78k	€74k
	e-Diesel	€50k	€54k	€54k
	Bio-CNG	€54k	€56k	€56k
	HVO	€45k	€49k	€49k

Appendix D: Truck residual value

Table D1. Summary of the trucks' estimated salvage values after 5 years of operation for model years 2023, 2030, and 2040.

Truck class	Technology	2023		2030		2040	
5-LH (500 km)	Diesel	€42k	28%	€43k	26%	€43k	26%
	BEV	€76k	22%	€53k	29%	€47k	30%
	FCV	€106k	22%	€62k	32%	€58k	33%
	H2-SI-ICE	€76k	30%	€64k	30%	€62k	31%
	H2-DF-ICE	€79k	30%	€68k	29%	€66k	29%
	e-Diesel	€42k	28%	€43k	26%	€43k	26%
	Bio-CNG	€47k	29%	€46k	27%	€46k	27%
	HVO	€42k	28%	€43k	26%	€43k	26%
5-LH (800 km)	Diesel	€48k	27%	€49k	26%	€49k	26%
	BEV	€72k	16%	€71k	32%	€66k	33%
	FCV	€125k	18%	€75k	33%	€71k	35%
	H2-SI-ICE	€95k	30%	€84k	31%	€80k	32%
	H2-DF-ICE	€104k	30%	€88k	30%	€84k	31%
	e-Diesel	€48k	27%	€49k	26%	€49k	26%
	Bio-CNG	€55k	29%	€55k	28%	€55k	28%
	HVO	€48k	27%	€49k	26%	€49k	26%
5-LH (1,000 km)	Diesel	€48k	27%	€49k	26%	€49k	26%
	BEV	€64k	14%	€81k	34%	€76k	35%
	FCV	€98k	14%	€79k	33%	€74k	35%
	H2-SI-ICE	€89k	28%	€87k	31%	€83k	32%
	H2-DF-ICE	€102k	29%	€96k	31%	€91k	32%
	e-Diesel	€48k	27%	€49k	26%	€49k	26%
	Bio-CNG	€55k	29%	€55k	28%	€55k	28%
	HVO	€48k	27%	€49k	26%	€49k	26%
4-RD	Diesel	€22k	27%	€23k	26%	€23k	26%
	BEV	€45k	24%	€35k	35%	€33k	37%
	FCV	€75k	24%	€37k	32%	€35k	36%
	H2-SI-ICE	€37k	30%	€31k	29%	€30k	30%
	H2-DF-ICE	€40k	29%	€35k	28%	€34k	29%
	e-Diesel	€22k	27%	€23k	26%	€23k	26%
	Bio-CNG	€24k	28%	€24k	27%	€23k	27%
	HVO	€22k	27%	€23k	26%	€23k	26%
3	Diesel	€21k	27%	€21k	26%	€21k	26%
	BEV	€34k	22%	€29k	34%	€27k	35%
	FCV	€43k	22%	€34k	33%	€32k	37%
	H2-SI-ICE	€34k	29%	€29k	30%	€28k	30%
	H2-DF-ICE	€36k	29%	€31k	28%	€30k	29%
	e-Diesel	€21k	27%	€21k	26%	€21k	26%
	Bio-CNG	€22k	28%	€22k	27%	€22k	27%
	HVO	€21k	27%	€21k	26%	€21k	26%
54	Diesel	€14k	28%	€14k	26%	€14k	26%
	BEV	€21k	22%	€19k	31%	€18k	33%
	FCV	€24k	14%	€25k	28%	€24k	32%
	H2-SI-ICE	€25k	31%	€21k	30%	€20k	31%
	H2-DF-ICE	€26k	30%	€22k	29%	€22k	29%
	e-Diesel	€14k	28%	€14k	26%	€14k	26%
	Bio-CNG	€16k	30%	€15k	27%	€15k	27%
	HVO	€12k	28%	€13k	26%	€13k	26%

Appendix E: Truck annual mileage

Table E1. Summary of vehicle annual kilometers traveled during their first 5 years of operation.

Truck Class	Five-year average annual mileage (km)	Year 1	Year 2	Year 3	Year 4	Year 5
5-LH (500 km)	119,000	130,297	130,297	120,506	109,962	105,252
5-LH (800 km)	158,000	173,000	173,000	160,000	146,000	139,747
5-LH (1,000 km)	201,000	220,082	220,082	203,544	185,734	177,779
4-RD	78,000	85,405	85,405	78,987	72,076	68,989
3	62,000	67,886	67,886	62,785	57,291	54,837
54	62,000	67,886	67,886	62,785	57,291	54,837

Appendix F: Motor fuel excise duties and road tolls

Table F1. Summary of motor fuel excise duties in European member states (European Commission, 2023d).

Member state	EUR cents/ liter Diesel	Refunds EUR cents/ liter Diesel	EUR cents/kg CNG
Belgium	45.55	20.5	0.00
Bulgaria	33.03	0	2.17
Czechia	34.45	0	15.00
Denmark	44.28	0	61.79
Germany	47.00	0	19.30
Estonia	37.20	0	5.35
Ireland	42.50	0	13.00
Greece	41.00	0	0.00
Spain	39.70	4.9	5.75
France	59.40	15.7	7.25
Croatia	35.30	0.3	0.00
Italy	61.70	21.41	0.50
Cyprus	33.00	0	13.00
Latvia	41.40	0	2.65
Lithuania	37.20	0	32.80
Luxembourg	42.88	0	8.39
Hungary	25.97	7.61	11.08
Netherlands	41.75	0	26.00
Austria	42.50	0	1.50
Poland	33.98	0	0.00
Portugal	32.42	0	12.45
Romania	33.00	0	15.90
Slovenia	34.97	11.32	14.35
Slovakia	36.80	0	13.00
Finland	53.30	0	29.25
Sweden	37.45	0	32.65

Table F2. Summary of truck road tolls in EU member states weighted based on road type.

Member state	54	3	4-RD	5-LH (500 km)	5-LH (800 km)	5-LH (1,000 km)
Belgium [a]	€0.102/km	€0.097/km	€0.154/km	€0.147/km	€0.140/km	€0.136/km
Bulgaria [b]	€0.018/km	€0.022/km	€0.026/km	€0.029/km	€0.030/km	€0.030/km
Czechia [c]	€0/km	€0.007/km	€0.065/km	€0.128/km	€0.144/km	€0.152/km
Denmark	Time-based vignette					
Germany [d]	€0/km	€0.020/km	€0.091/km	€0.152/km	€0.171/km	€0.181/km
Estonia	Time-based vignette					
Ireland	Time-based vignette					
Greece [e]	€0/km	€0.038/km	€0.130/km	€0.208/km	€0.234/km	€0.247/km
Spain [e]	€0/km	€0.030/km	€0.080/km	€0.128/km	€0.144/km	€0.152/km
France [e]	€0/km	€0.048/km	€0.160/km	€0.256/km	€0.288/km	€0.304/km
Croatia	Time-based vignette					
Italy [f]	€0/km	€0.016/km	€0.050/km	€0.080/km	€0.090/km	€0.095/km
Cyprus	No tolls					
Latvia	Time-based vignette					
Lithuania	Time-based vignette					
Luxembourg	Time-based vignette					
Hungary [g]	€0.039/km	€0.077/km	€0.186/km	€0.380/km	€0.395/km	€0.403/km
Netherlands	Time-based vignette					
Austria	€0/km	€0.042/km	€0.145/km	€0.352/km	€0.396/km	€0.418/km
Poland [i]	€0.022/km	€0.041/km	€0.057/km	€0.068/km	€0.069/km	€0.070/km
Portugal [e]	€0/km	€0.030/km	€0.105/km	€0.168/km	€0.189/km	€0.200/km
Romania	Time-based vignette					
Slovenia [e]	€0/km	€0.038/km	€0.190/km	€0.304/km	€0.342/km	€0.361/km
Slovakia [h]	€0.085/km	€0.085/km	€0.190/km	€0.198/km	€0.198/km	€0.198/km
Finland	No tolls					
Sweden	Time-based vignette					

Note: The tolling system in some EU member states consists of different rates for highways and local/regional roads. We assume the following shares of vkt on each type of road for the different truck classes: Class 54: 100% local, Class 3: 80% local – 20% highway, Class 4-RD: 50% local – 50% highway, Class 5-LH (500 km): 80% highway – 20% local, Class 5-LH (800 km): 90% highway – 10% local, Class 5-LH (1,000 km): 95% highway – 5% local.

[a] Viapass (2019)

[b] Администратор (2022)

[c] Myto (2021)

[d] Impargo (2023).

[e] Schroten et al. (2019).

[f] Autostrade per l'Italia (2021).

[g] Effective as of October 1st, 2023. Hu-Go (2023)

[h] Emyto (2023)

[i] e-Toll (2023)

Appendix G: TCO results for selected truck classes

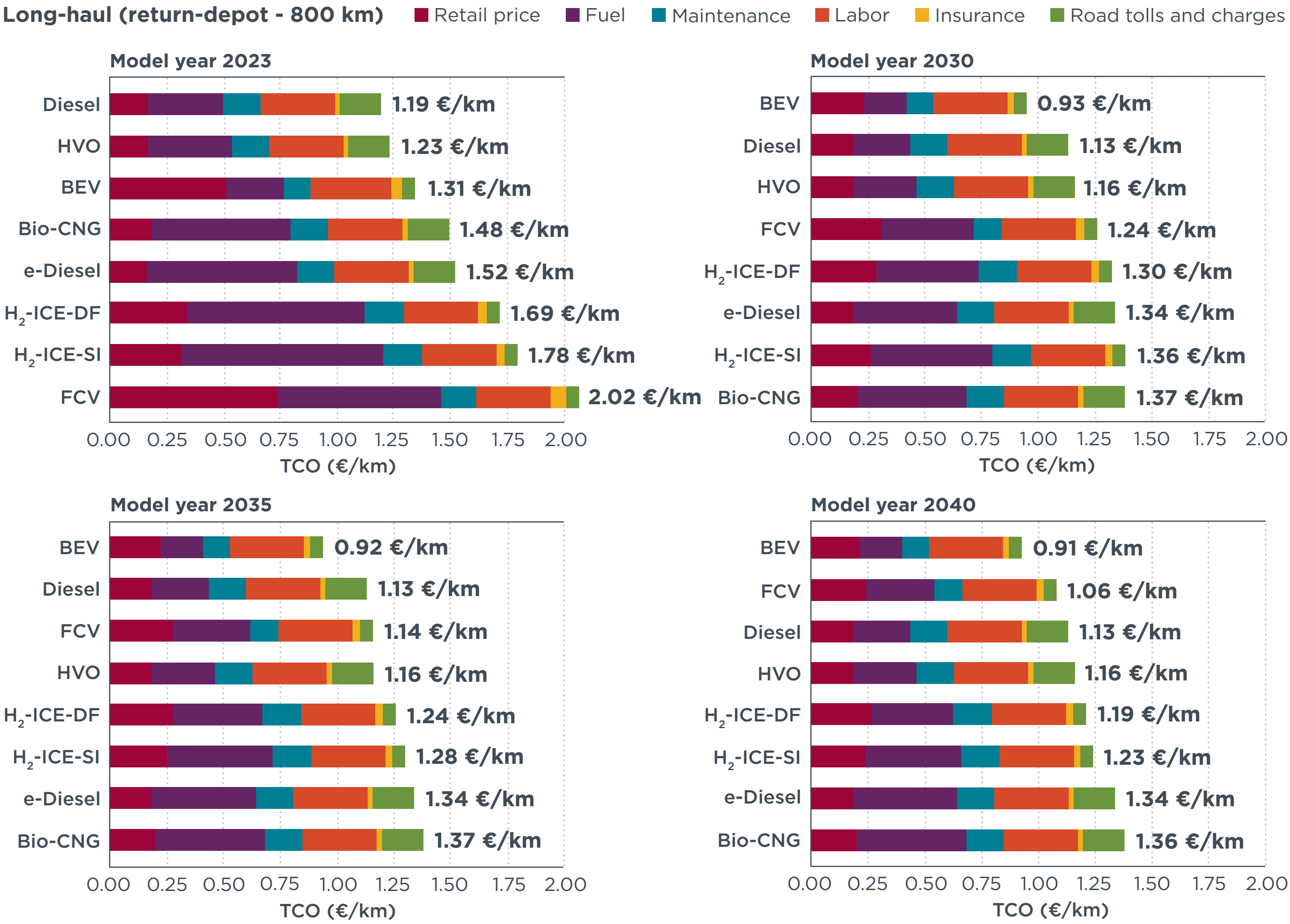


Figure G1. TCO breakdown for long-haul truck return-depot 800 km case for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

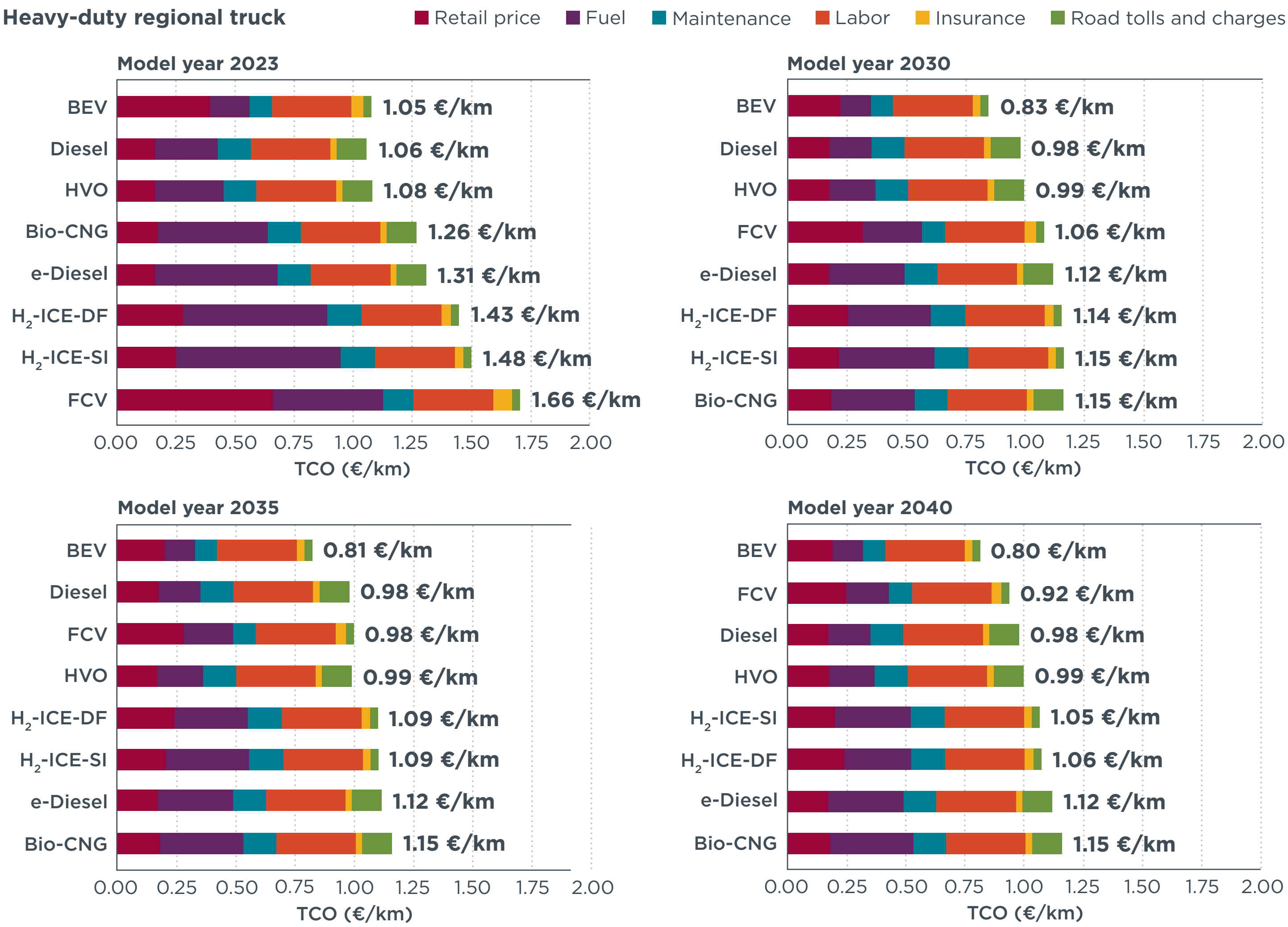


Figure G2. TCO breakdown for heavy-duty regional delivery truck for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

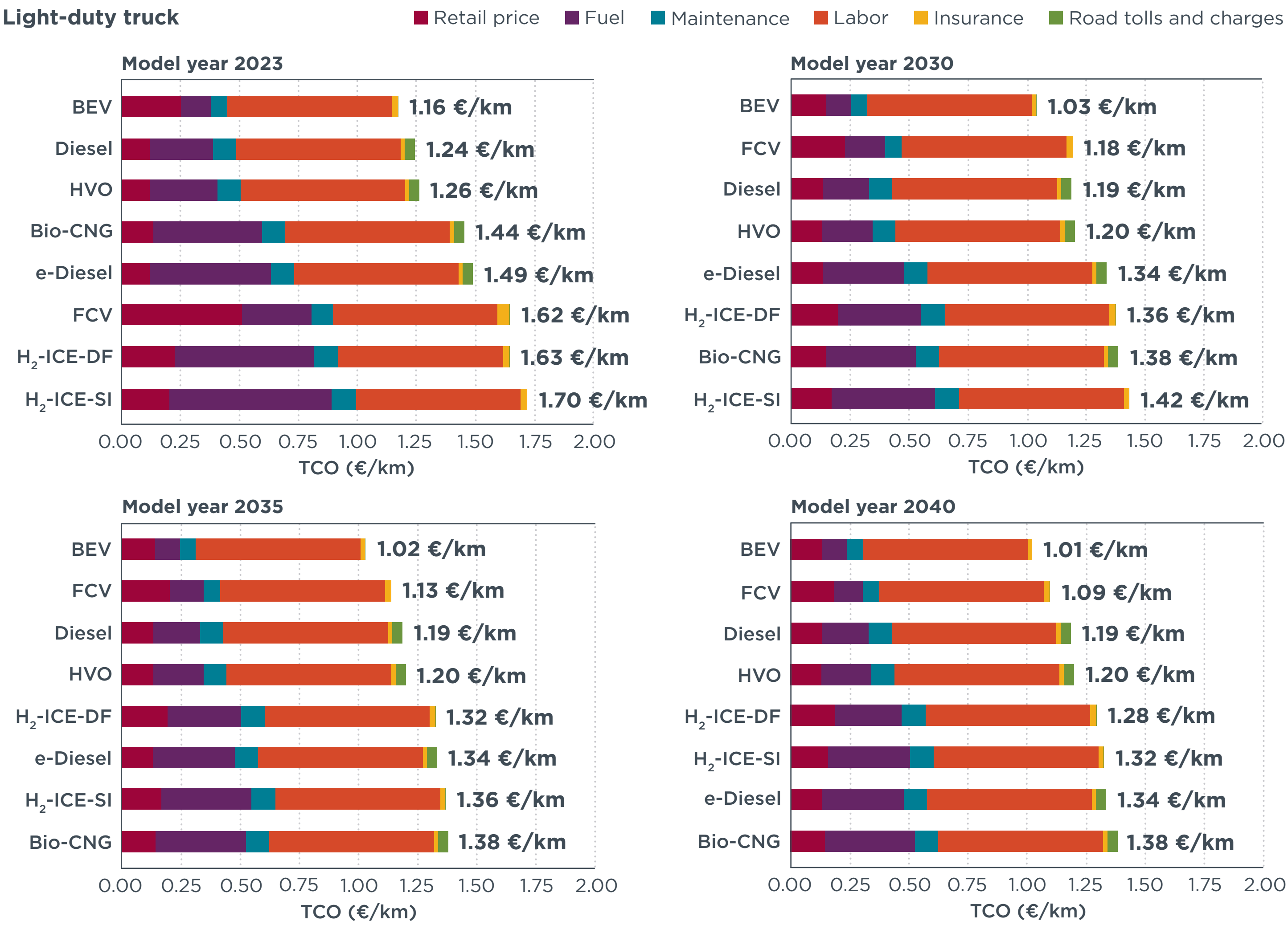


Figure G3. TCO breakdown for light-duty urban truck for different powertrain technologies for model years 2023, 2030, 2035, and 2040.

Addendum

As highlighted by Zhou, Searle, and Pavlenko (2022), the electricity grid is unlikely to be 100% renewable in the near term; the above analysis thus assumed that the green hydrogen production facility would pursue a long-term electricity purchase agreement with a renewable electricity provider. This is an example of a Power Purchase Agreement (PPA). The European Union recently released a delegated act that requires such PPAs and additional steps to ensure additionality in most grid regions, and the cost impact of this remains uncertain.[1]

This addendum provides an additional scenario regarding the charging costs of battery electric trucks. Here, a similar PPA is modeled for the battery charging station, and the scenario considers more optimistic electricity costs than those projected in the central scenario above. In addition, this new hypothetical scenario ignores the differences in network fees and taxes for different consumers' bandwidths and usage profiles. All other total cost of ownership (TCO) inputs and assumptions remain the same.

The levelized cost of renewable electricity production between 2020 and 2040 is extracted from Zhou et al. (2022); to that we add the country-specific network costs and all non-recoverable taxes and levies, as highlighted in the same study. Finally, we add the charging infrastructure and grid upgrade levelized costs as mentioned in the analysis above. Addendum Table 1 details the new charging costs per truck class in 2030 and 2040.

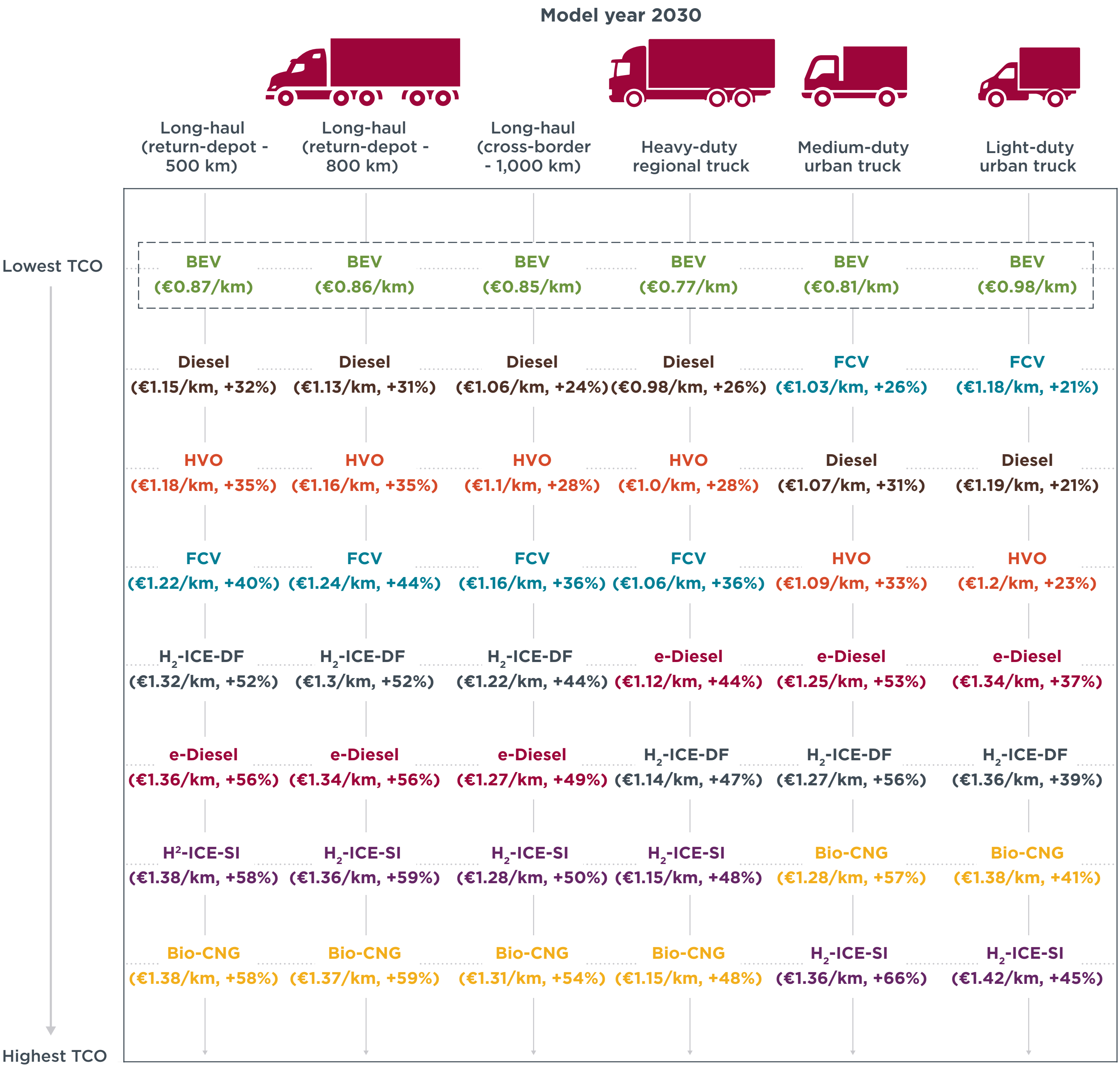
Addendum Table 1. Charging costs in €/kWh per truck class, assuming the charging stations acquire electricity through a PPA for renewable electricity and the same grid fees and taxes for all consumer profiles.

Vehicle class	2030	2040
54	0.117	0.114
3	0.116	0.113
4-RD	0.116	0.113
5-LH (500)	0.123	0.120
5-LH (800)	0.123	0.120
5-LH (1,000)	0.160	0.157

Addendum Figure 1 is a new ranking of the TCO performance of different truck classes and powertrain technologies for model year 2030 using the battery electric truck costs from the additional scenario. It shows the TCO of each decarbonization pathway and truck class, and the percentage difference in TCO relative to the least-cost decarbonization pathway. With the lower electricity prices considered in this scenario and the subsequent lower charging costs relative to our central scenario, the TCO of battery electric trucks is lower and their economic advantage over all other decarbonization pathways is wider.

Addendum Figure 2 presents the same TCO calculations for model year 2040.

1 For more on these rules, see European Commission, "Commission Sets Out Rules for Renewable Hydrogen," February 13, 2023, https://ec.europa.eu/commission/presscorner/detail/en/IP_23_594.



Addendum Figure 1. Ranking of the TCO performance of different truck classes and powertrain technologies for model year 2030 under the new scenario for battery electric trucks. The figure shows the TCO of each decarbonization pathway and truck class and the percentage difference in TCO relative to the least-cost decarbonization pathway.

Model year 2040

	Long-haul (return-depot - 500 km)	Long-haul (return-depot - 800 km)	Long-haul (cross-border - 1,000 km)	Heavy-duty regional truck	Medium-duty urban truck	Light-duty urban truck
Lowest TCO	BEV (€0.85/km)	BEV (€0.84/km)	BEV (€0.83/km)	BEV (€0.74/km)	BEV (€0.78/km)	BEV (€0.96/km)
	FCV (€1.08/km, +26%)	FCV (€1.06/km, +27%)	FCV (€1.0/km, +20%)	FCV (€0.92/km, +23%)	FCV (€0.92/km, +16%)	FCV (€1.09/km, +13%)
	Diesel (€1.15/km, +35%)	Diesel (€1.13/km, +35%)	Diesel (€1.06/km, +27%)	Diesel (€0.98/km, +31%)	Diesel (€1.07/km, +36%)	Diesel (€1.19/km, +24%)
	HVO (€1.18/km, +38%)	HVO (€1.16/km, +38%)	HVO (€1.1/km, +32%)	HVO (€1.0/km, +33%)	HVO (€1.09/km, +38%)	HVO (€1.2/km, +25%)
	H_2-ICE-DF (€1.22/km, +42%)	H_2-ICE-DF (€1.19/km, +42%)	H_2-ICE-DF (€1.11/km, +34%)	H_2-ICE-SI (€1.05/km, +41%)	H_2-ICE-DF (€1.18/km, +50%)	H_2-ICE-DF (€1.28/km, +34%)
	H_2-ICE-SI (€1.24/km, +45%)	H_2-ICE-SI (€1.23/km, +46%)	H_2-ICE-SI (€1.15/km, +38%)	H_2-ICE-DF (€1.06/km, +42%)	H_2-ICE-SI (€1.23/km, +56%)	H_2-ICE-SI (€1.32/km, +37%)
	e-Diesel (€1.36/km, +59%)	e-Diesel (€1.34/km, +60%)	e-Diesel (€1.27/km, +54%)	e-Diesel (€1.12/km, +50%)	e-Diesel (€1.25/km, +59%)	e-Diesel (€1.34/km, +39%)
	Bio-CNG (€1.38/km, +61%)	Bio-CNG (€1.36/km, +63%)	Bio-CNG (€1.31/km, +58%)	Bio-CNG (€1.15/km, +54%)	Bio-CNG (€1.28/km, +63%)	Bio-CNG (€1.38/km, +43%)
Highest TCO						

Addendum Figure 2. Ranking of the TCO performance of different truck classes and powertrain technologies for model year 2040 under the new scenario for battery electric trucks. The figure shows the TCO of each decarbonization pathway and truck class and the percentage difference in TCO relative to the least-cost decarbonization pathway.