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THE EUROPEAN HEAVY-DUTY VEHICLE MARKET UNTIL 2040: ANALYSIS OF DECARBONIZATION PATHWAYS

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EXECUTIVE SUMMARY

The European Union has set a goal of net-zero greenhouse gas (GHG) emissions by mid-century, as stated in the European Climate Law. Heavy-duty vehicles (HDVs) will play a vital role during this transition, given their significant contribution to road transport GHG emissions and the continuous increase in freight activity. The European Commission will revise the CO_2 standards for new HDVs by the beginning of 2023. The current CO_2 reduction targets mandate a 15% reduction in CO_2 emissions by 2025 and 30% by 2030, relative to the 2019/2020 baseline period, and propose no CO_2 reduction targets beyond 2030. These targets fall short of the EU's short- and long-term climate goals and must be reviewed with higher CO_2 reduction ambition.

This paper assesses the cost-effectiveness of different CO_2 reduction strategies for the HDV sector. We examine the required HDV technology market share to meet the mandated CO_2 reduction targets and the corresponding decarbonization cost. In addition, we propose HDV CO_2 reduction targets up to 2040. The study focuses on four main truck technologies: diesel, liquified-natural gas, battery-electric, and hydrogen fuel-cell trucks. We quantify the manufacturers' compliance costs and examine the impact of different decarbonization strategies on the consumer and society by conducting a cost-benefit analysis.

The study evaluates two main scenarios for the HDV CO_2 reduction between 2030 and 2040. The first scenario is the currently adopted CO_2 reduction targets. No official targets are set beyond 2030, so we assume the 30% reduction target will remain in place until 2040. The second scenario considers the announcements made by the primary HDV manufacturers in the EU regarding their zero-emission truck sales between 2030 and 2040. Our modeling indicates that CO_2 reduction targets of 60% by 2030, 90% by 2035, and 100% by 2040 would be needed for the regulation to cement the industry's voluntary pledges.

The required technology market shares to meet the CO_2 reduction targets differ between the mentioned scenarios. Those targets could be achieved by improving the current internal combustion engine (ICE) truck technologies or increasing the shares of zero-emission trucks, namely battery-electric and hydrogen fuel-cell trucks. An optimization algorithm is developed to determine the optimal technology market share and needed ICE technology improvement across the currently certified HDV groups to minimize manufacturers' compliance costs. Finally, the study quantifies the consumer and societal cost savings under the two CO_2 reduction scenarios based on the resulting technology market shares.

We arrive at the following main findings:

» **Battery-electric trucks are the most cost-effective technology for meeting the HDV CO_2 reduction targets**. Battery-electric trucks provide significant CO_2 reductions at relatively low additional direct manufacturing costs. Under the proposed high-ambition scenario, the cost-optimal technology market share to meet the 60% CO_2 reduction target by 2030 involves transitioning to battery-electric technologies for most truck segments, including long-haul trucks with daily driving mileages up to 500 km. Long-haul trucks with daily mileages above 500 km will be expensive to electrify by 2030 and will still rely on improved diesel technologies.

By 2040, the 100% CO_2 reduction target allows only the registration of zero-emission trucks, i.e., battery-electric and hydrogen fuel-cell technologies. From a compliance cost perspective, battery-electric trucks will be the cheaper technology for most segments, including long-haul trucks with driving mileages up to 500 km. For long-haul trucks with driving mileages above 500 km, the manufacturing costs of both zero-emission technologies will be very similar. However, the consumer and societal cost-savings will be at least 30% higher if these long-haul trucks are decarbonized using battery-electric technologies, mainly due to the higher operating expenses of fuel-cell trucks, driven by the price of hydrogen fuel, and their lower energy efficiency relative to their battery-electric counterparts.

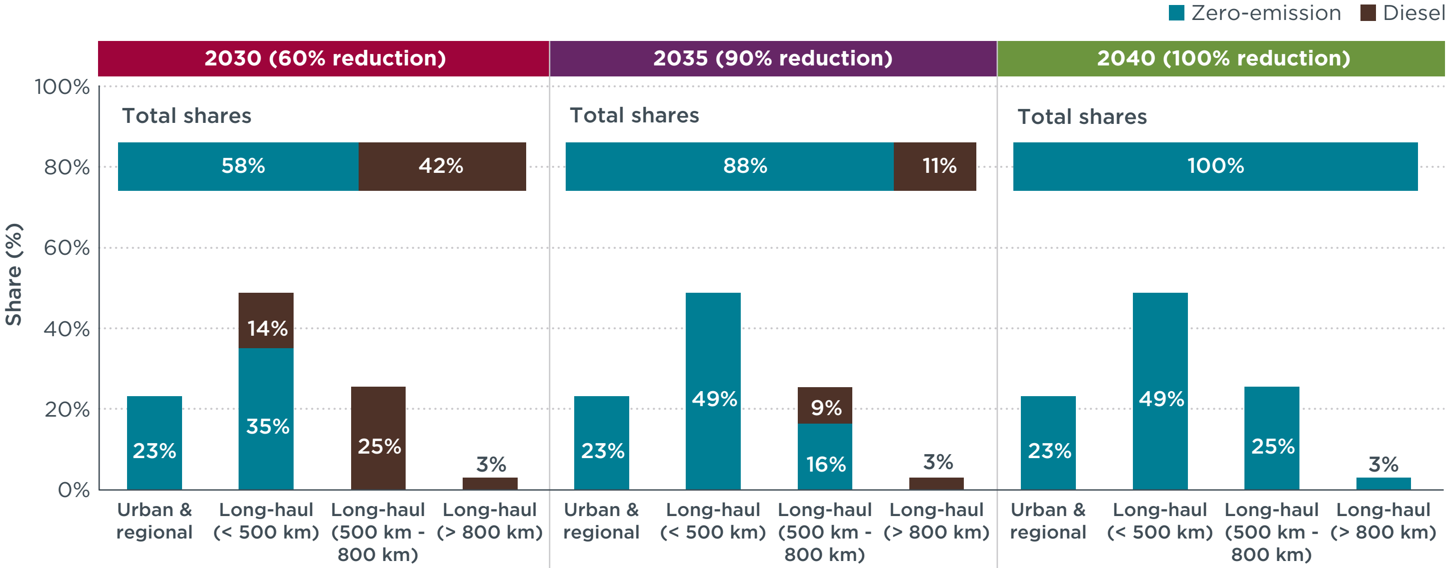

Figure ES1. Heavy-duty vehicle technology market share evolution between 2030 and 2040 to meet the proposed CO_2 reduction targets (2030: 60%, 2035: 90%, and 2040: 100%).

» **The most cost-effective decarbonization pathway involves a gradual shift towards truck electrification as of 2030 without fully exploiting the CO_2 reduction potential of diesel trucks.** For long-haul tractor-trailers, the most cost-effective decarbonization pathway includes improving the diesel technology to up to 18.5% reduction in CO_2 by 2030, which is much lower than the technology's CO_2 reduction potential of over 30%. After 2030, more stringent CO_2 reduction targets can be met by gradually increasing the share of battery-electric trucks until full decarbonization is reached by 2040 (Figure ES2).

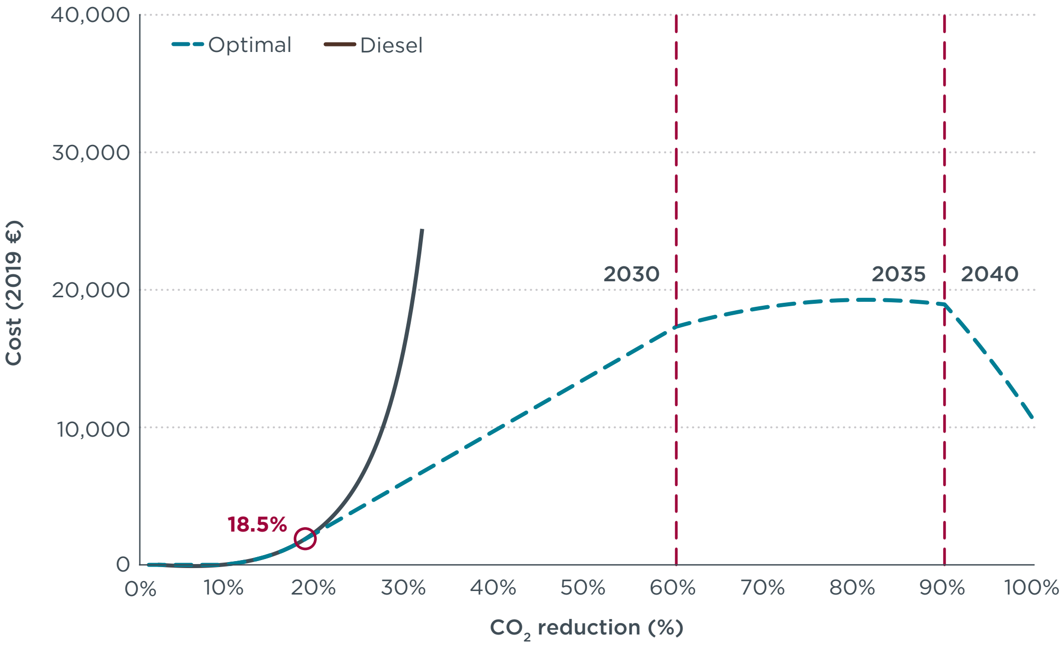

Figure ES2. Optimal CO_2 cost curve for long-haul tractor-trailers (VECTO group 5-LH).

» **Ambitious CO_2 reduction targets will increase the average direct manufacturing costs. Nonetheless, the resulting cost savings for the consumer and society are substantial and counterweigh the necessary investment.** By 2030**,** the proposed 60% CO_2 reduction target will result in a compliance cost of €12,473 per vehicle. By 2040, this is expected to increase slightly to €12,487 per vehicle despite the higher CO_2 reduction target of 100%, mainly driven by a reduction in the prices of zero-emission technologies (Figure ES3).

The consumer and societal cost savings are significantly higher under the proposed CO_2 reduction scenario than the currently adopted low-ambition policies. By 2030, the high-ambition 60% CO_2 reduction target can provide average cost savings in the range of €50,000–€120,000 per vehicle for the first and second users, depending on the diesel fuel prices. This is significantly higher than the cost savings obtained under the currently adopted policies, which is ranging between €30,000 and €60,000 per vehicle. By 2040, these consumer cost savings are expected to increase under the 100% CO_2 reduction target, ranging between €100,000 and €200,000 per vehicle. In addition, societal cost savings are two to three times higher under the proposed CO_2 reduction scenario than the currently adopted policies. In addition to the significant savings from a total cost of ownership perspective over the vehicle lifetime, the CO_2 avoidance cost to society further increases the societal cost savings under more ambitious CO_2 reduction targets, as shown in Figure ES3.

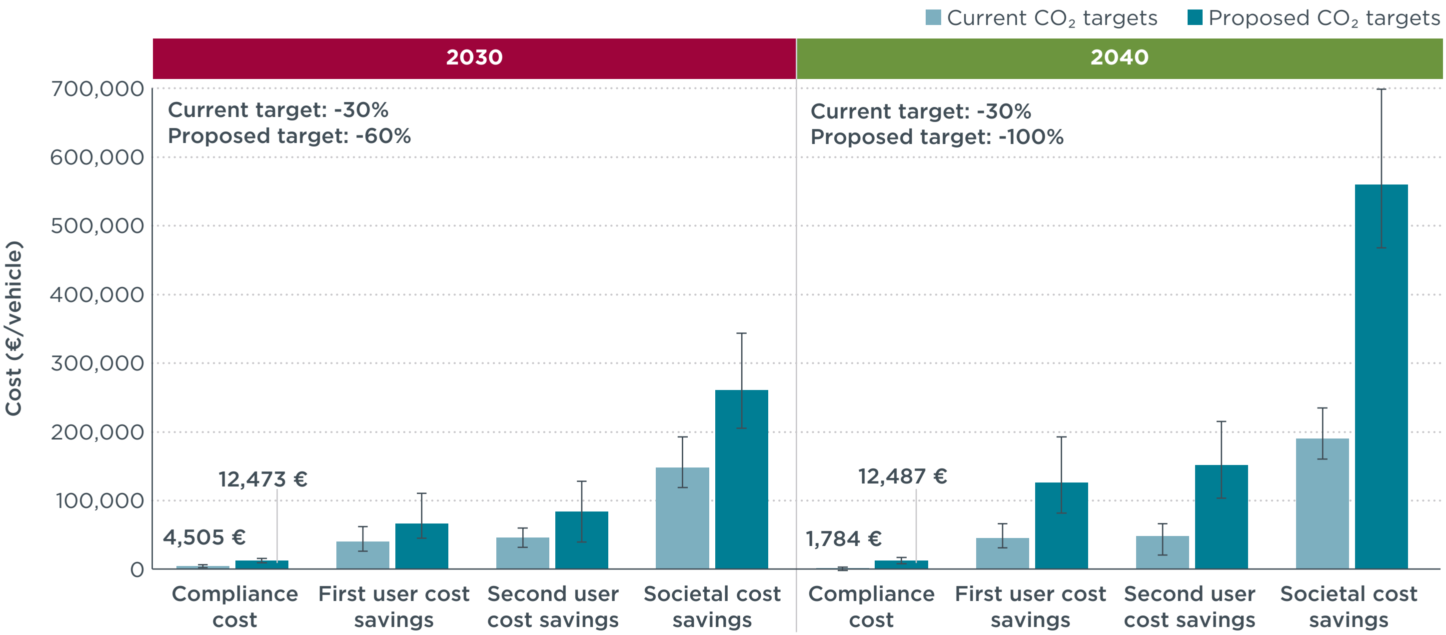

Figure ES3. Summary of the compliance costs and cost savings from the first user, second user, and societal perspectives for different CO_2 reduction scenarios between 2030 and 2040.

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ADMC	Additional direct manufacturing cost
BET	Battery-electric truck
CAPEX	Capital expenses
CO_2	Carbon dioxide
C	Construction
DMC	Direct manufacturing cost
FCET	Fuel-cell electric truck
GHG	Greenhouse gas
HDV	Heavy-duty vehicle
ICE	Internal combustion engine
LH	Long-haul
LNG	Liquified natural gas
MPW	Mileage and payload weight
MU	Municipal utility
OPEX	Operational expenses
RD	Regional delivery
SLSQP	Sequential least squares programming
TTW	Tank-to-wheel
UD	Urban delivery
VECTO	Vehicle Energy Consumption Calculation Tool
WTT	Well-to-tank
ZE	Zero-emission

INTRODUCTION

The European Union has committed to a carbon-neutral economy by mid-century, as indicated in the European Climate Law, with a short-term target of a 55% reduction in greenhouse gas emissions (GHG) by 2030 compared to 1990 (European Commission, 2021). The transport sector, responsible for more than a quarter of the EU's GHG emissions (Heinrich-Böll-Stiftung European Union, 2021), is subject to a 90% reduction in GHG emissions relative to the 1990 levels (European Commission, 2020). The heavy-duty vehicle (HDV) sector is among the most challenging to decarbonize, given the continuous increase in road freight activity and the negligible share of low- and zero-emission vehicles within the segment (Basma & Rodríguez, 2021), mainly driven by the nascency of the regulatory efforts to curb the segment's GHG emissions.

The European HDV CO_2 standards, first proposed in 2019, mandate a 15% average CO_2 reduction of new truck registrations in the EU by 2025 relative to the 2019/2020 reporting year and a 30% reduction by 2030. With the currently adopted CO_2 reduction targets, HDV CO_2 emissions in the EU are projected to increase by 8% in 2050 relative to 2019, driven by the increase in road freight activity offsetting the obtained CO_2 reduction at the vehicle level (Mulholland et al., 2022). Thus, more stringent CO_2 reduction targets are needed for the EU to reach its short- and long-term climate goals.

The CO_2 standards will be reviewed by the beginning of 2023, providing an opportunity to increase the HDV CO_2 reduction ambition in the short term and propose new targets beyond 2030. The stringency of the currently adopted CO_2 standards was set by examining the CO_2 reduction potential of conventional powertrain technologies, namely diesel and natural gas internal combustion engine (ICE) technologies (Krause & Donati, 2018). However, the recent developments in zero-emission (ZE) technologies, namely battery-electric and hydrogen fuel cell trucks, can help achieve higher CO_2 reductions and provide an opportunity to increase the ambition of the European HDV CO_2 standards.

This paper aims to inform the upcoming review of the HDV CO_2 standards by assessing the cost-effectiveness of different CO_2 reduction strategies. We present the HDV technology market share needed to meet a specific CO_2 reduction target in a given year and the corresponding decarbonization cost. The study looks at the European HDV market in the 2030–2040 timeframe, focusing on the currently certified HDV segments according to the EU regulation 2017/2400 (European Commission, 2017). We analyze the internal combustion engine HDVs' CO_2 reduction potential in the mentioned timeframe and project the corresponding technology cost. We also quantify the ZE-HDV technology costs and forecast these costs up to 2040 based on detailed assumptions and modeling regarding vehicle energy efficiency and costs. The study examines two different CO_2 reduction scenarios, including the currently mandated targets and another scenario with a higher CO_2 reduction ambition. These scenarios are derived from a previous ICCT study (Mulholland et al., 2022). The study also considers a cost-benefit analysis examined from both the consumer and societal perspectives.

METHODOLOGY AND DATA

FRAMEWORK

The proposed methodology aims to identify the most cost-effective technology market share across the different HDV truck segments between 2030 and 2040 that will meet the HDV CO_2 reduction targets in the EU. The methodology is comprised of several steps, as will be detailed in the upcoming sections.

Heavy-duty truck segments of interest are first introduced, including all certified truck groups 1-5, 9-12, and 16, and VECTO group 0. The current market share of each truck group in the EU is presented, further segmenting the truck groups based on their mission profiles.

Then, the diesel and liquefied natural gas (LNG) truck technologies are introduced, referred to as ICE truck technologies. The CO_2 reduction potential of each technology and the associated costs for each truck segment are presented based on the CO_2 technology cost curves developed by Krause and Donati (2018) within the scope of the 2019 EU HDV CO_2 standards impact assessment study. The mentioned study solely focused on truck groups 4, 5, 9, and 10 in long-haul and regional-delivery mission profiles. For this study, we develop the CO_2 technology cost curves for the other truck groups and mission profiles based on the methodology proposed in Krause and Donati (2018) and using VECTO, the Vehicle Energy Consumption Calculation Tool (VECTO, 2017).

The ZE HDV technologies are then presented, focusing on battery-electric and fuel-cell truck technologies. The tailpipe CO_2 reduction potential of these technologies is 100% compared to diesel or LNG engines. However, the technology cost highly fluctuates across the different truck groups, driven by the size of their power units and energy storage systems (battery, hydrogen tank, and fuel cell stack). A detailed cost breakdown analysis is used to construct the direct manufacturing cost and retail price of ZE HDV trucks for each of the groups considered in this study.

Scenarios for CO_2 reduction targets are presented, providing several levels of stringency for the currently deployed targets. The stringency of the targets directly drives the technology market share, as discussed in the section HDV fleet CO_2 cost curves.

Finally, the optimal technology market share across the different truck groups is identified using an optimization-based methodology, minimizing the additional direct manufacturing costs to meet the HDV CO_2 reduction targets in the EU. Based on the truck technologies' CO_2 reduction potential and the additional incurred costs, in addition to the CO_2 reduction targets scenarios, the optimization methodology provides the HDV fleet cost curves between 2030 and 2040.

Figure 1 summarizes the methodology framework.

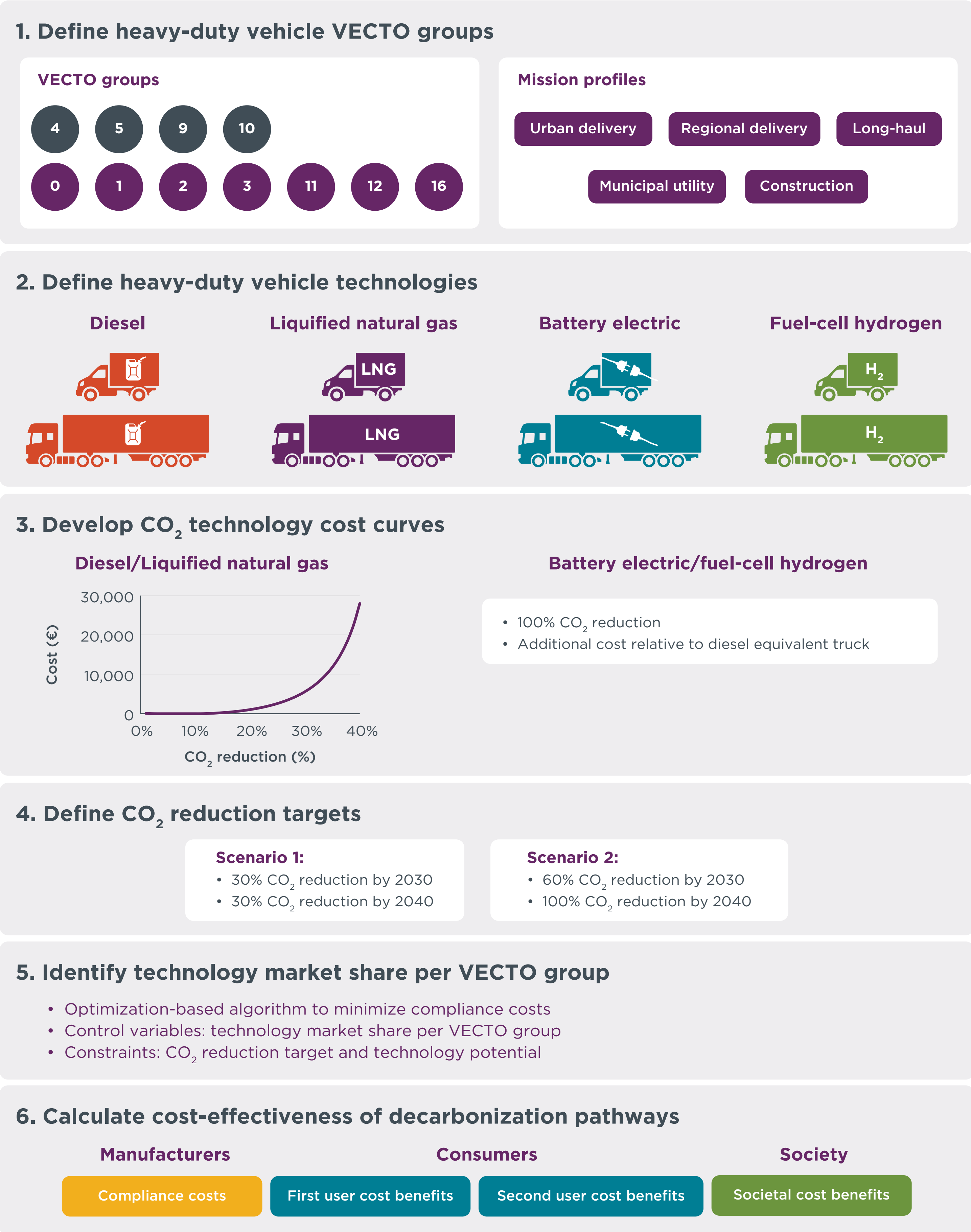

Figure 1. HDV fleet CO_2 cost curves method framework

HDV VECTO GROUPS

The impact assessment study for the EU Commission regulation regarding the CO_2 standards for HDVs focuses on truck groups 4, 5, 9, and 10 and two mission profiles per truck: (1) long-haul and (2) regional delivery mission profiles (European Commission, 2019b). According to data from IHS Markit Global S.à.r.l.,[1] the 2020 new registrations market share of these groups is almost 59%, implying that nearly 41% of new truck registrations in the EU are not considered in the EU HDV CO_2 standards impact assessment study. In this study, we cover the truck groups included in the impact assessment in addition to truck group 0 and all currently certified groups (1, 2, 3, 11, 12, and 16),[2] covering more than 94% of the EU truck market. Truck groups 6, 7, 8, 13, 14, 15, and 17 are not considered in this study, primarily because they are not certified and thus not defined in VECTO, and the market share of those groups combined was less than 6% of annual registrations in 2021. In addition, this study investigates the different mission profiles for each truck group, including long-haul (LH), regional delivery (RD), urban delivery (UD), municipal utility (MU), and construction (C) mission profiles. Table 1 summarizes the considered truck groups in this study. Figure 2 shows the certified truck registration share by VECTO group. These shares are not the absolute shares out of all HDV groups but the relative shares considering only certified groups.

Table 1. Heavy-duty vehicle market segmentation in the European Union

VECTO group	Axle type	Chassis configuration	Gross vehicle weight (tonnes)	Covered by HDV CO_2 standards
0	4x2	Rigid	< 7.5	No
1	4x2	Rigid/Tractor	7.5 - 10	No
2	4x2	Rigid/Tractor	10 - 12	No
3	4x2	Rigid/Tractor	12 - 16	No
4	4x2	Rigid	> 16	Yes
5	4x2	Tractor	> 16	Yes
9	6x2	Rigid	All weights	Yes
10	6x2	Tractor	All weights	Yes
11	6x4	Rigid	All weights	No
12	6x4	Tractor	All weights	No
16	8x4	Rigid	All weights	No

1 Content supplied by IHS Markit Global S.à.r.l.;

2 Truck group 0 is an unofficial group that is used in this report to represent rigid trucks with GVW between 3.5 and 7.5 tonnes.

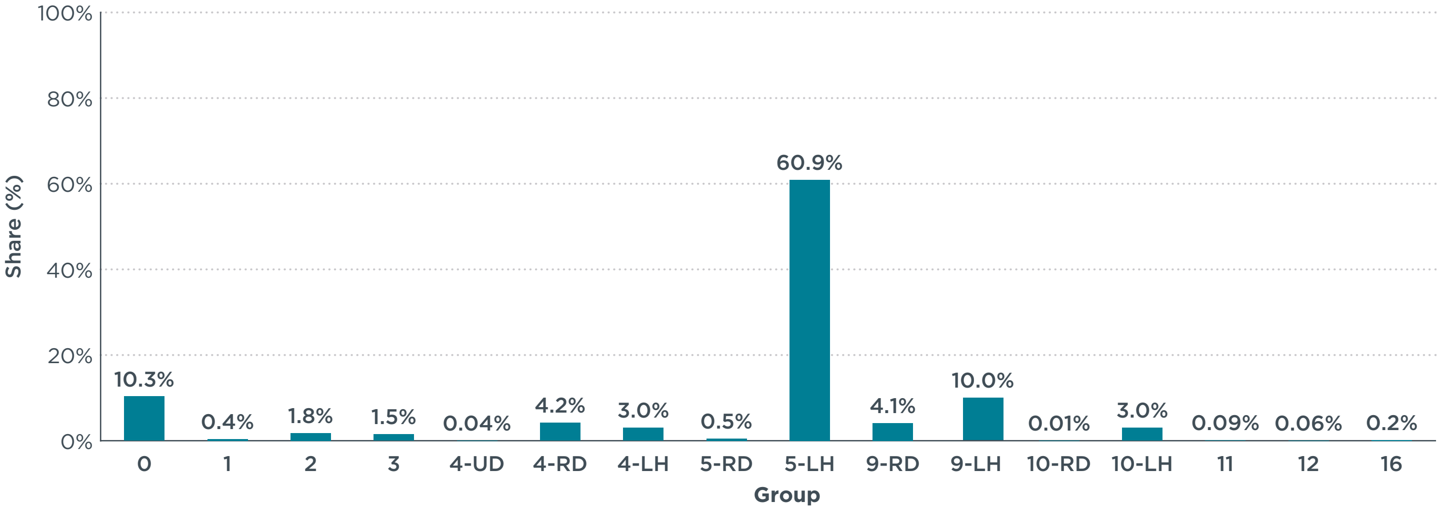

Figure 2. Certified Trucks relative share by VECTO group in 2020 according to IHS Markit Global S.à.r.l. These shares are not the absolute shares out of all HDV groups but rather the relative shares considering only certified groups and group 0.

TRUCK ICE TECHNOLOGIES: DIESEL AND LNG

Within the scope of the EU HDV CO_2 standards impact assessment study, the CO_2 technology cost curves of truck groups 4, 5, 9, and 10 were developed by Krause and Donati (2018) for the LH and RD truck mission profiles for diesel and LNG vehicle technologies. In this section, we adopt the same approach to develop the CO_2 technology cost curves for truck groups 0, 1, 2, 3, 11, 12, and 16, and their corresponding mission profiles.

Each truck group differs in its chassis type, maximum laden mass, curb mass, aerodynamic drag and surface area, rolling resistance coefficients, engine power, and many other parameters that are documented in VECTO and summarized in Table A1, Table A2, and Table A3 in the appendix. These parameters impact the truck fuel consumption and CO_2 reduction potential. Table A6 in the appendix summarizes the simulated diesel fuel consumption for an average 2016 vehicle for all considered truck groups and over several mission profiles and payloads using VECTO. The obtained diesel fuel consumption values are validated against the data reported in the impact assessment support study (TNO, 2018) for groups 4, 5, 9, and 10. The percentage error difference is less than 2% for groups 4, 9, and 10, while only group 5 records a percentage error difference reaching 5% over the RD mission profile. This is within the uncertainty range reported in the study of around +/- 7% (TNO, 2018).

To estimate the average energy consumption of a diesel truck in 2025, several technology packages are implemented to reflect the diesel technology improvement. These technology packages include improved truck aerodynamics, rolling resistance (tires), chassis light-weighting, engine efficiency, waste heat recovery, and auxiliary efficiency. These technology packages are well documented in TNO (2018) where each technology package impacts the truck fuel consumption differently. The hybridization technology package is not considered, as there have been no announcements from truck manufacturers regarding any large-scale commercialization of hybrid models.

It is assumed that all truck groups will have a similar technology penetration rate to groups 4, 5, 9, and 10. Rigid truck groups 0, 1, 2, and 3 have a similar technology penetration rate to rigid truck group 4. In addition, rigid truck groups 11 and 16 are assumed to have similar technology penetration rates to group 9 rigid trucks, while tractor trucks group 12 is considered similar to group 10. A new set of simulations is conducted in VECTO while implementing the mentioned technology packages to obtain the maximum CO_2 reduction potential for each truck group by 2025. By 2030, the reduction potential will increase by 5%, and cost development will yield close to a 10% reduction in the technology package cost. In addition, a 100% technology penetration rate is assumed by 2030. Figure 3 summarizes the diesel trucks' maximum CO_2 reduction potential by 2030 relative to a 2016 diesel truck. The data is summarized in Table A7.

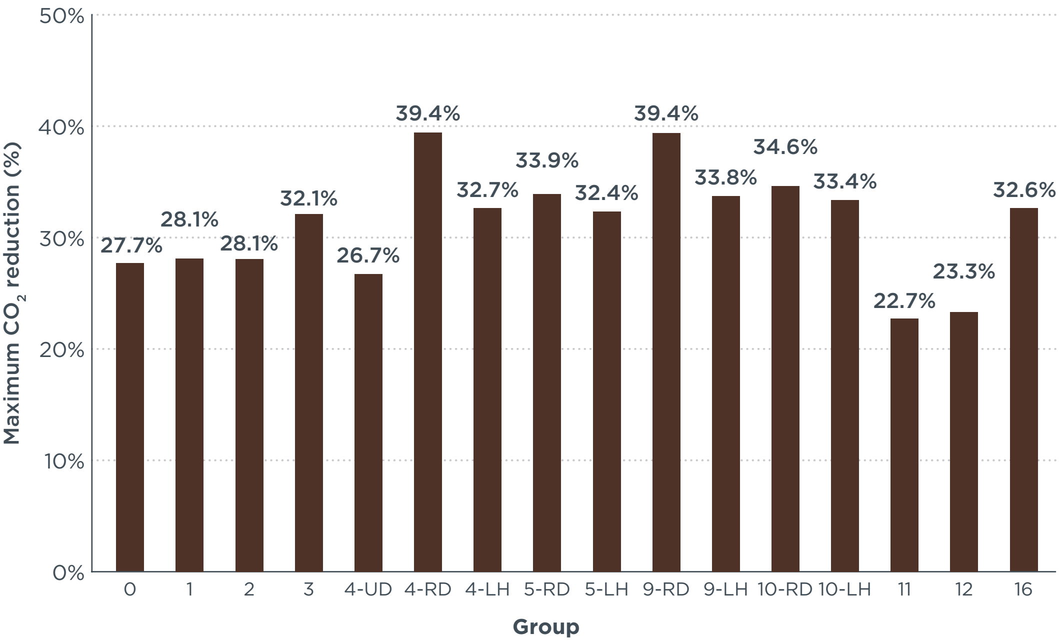

Figure 3. Diesel trucks' maximum CO_2 reduction potential by 2030 relative to a 2016 diesel truck

The CO_2 technology cost curves, or costs as a function of CO_2 reduction, for all truck groups follow a similar reciprocal function as presented by Krause and Donati (2018). Truck groups with the same technology penetration rates will incur similar costs, but their maximum CO_2 reduction potential is different. In addition, the CO_2 technology cost curves were developed based on a 2016 average diesel truck. We correct the CO_2 technology cost curves relative to a 2019 average diesel truck since it is the base year of the EU HDV CO_2 standards, considering the technology packages implemented between 2016 and 2019 for diesel trucks and the corresponding resulting CO_2 reduction. The CO_2 reduction between 2016 and 2019 is assumed to be 0.5%. Moreover, the CO_2 technology cost curves expressed in 2015 Euros were converted to 2019 Euros considering a 4.6% inflation rate between 2015 and 2019 in the EU (European Central Bank, 2021).

Figure 4 and Figure 5 show the CO_2 technology cost curves in 2030 for diesel and LNG trucks, respectively. The CO_2 cost curves data are summarized in the appendix in Table A11, Table A12, Table A13, and Table A14.

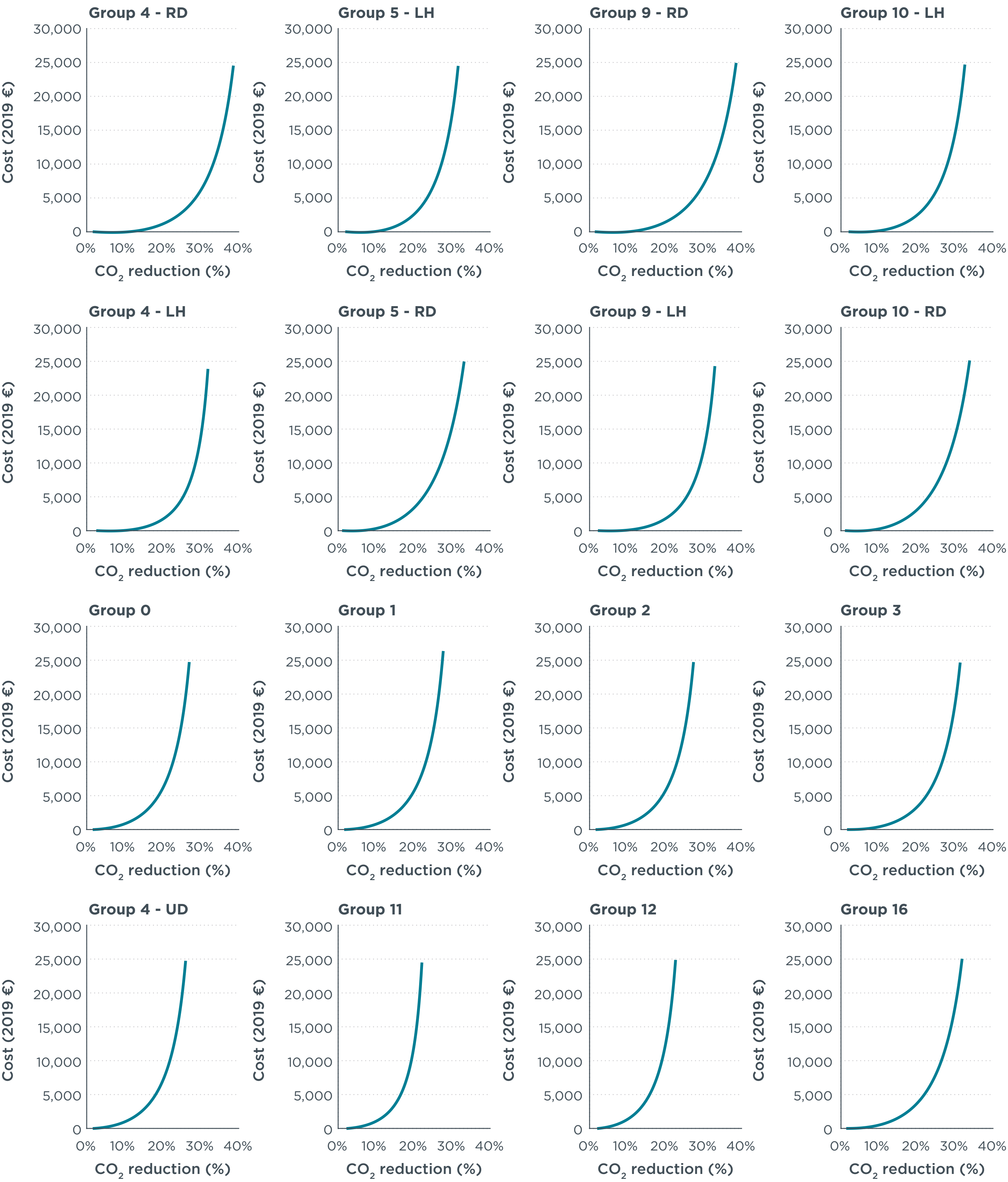

Figure 4. CO_2 technology cost curves for diesel trucks in 2030.

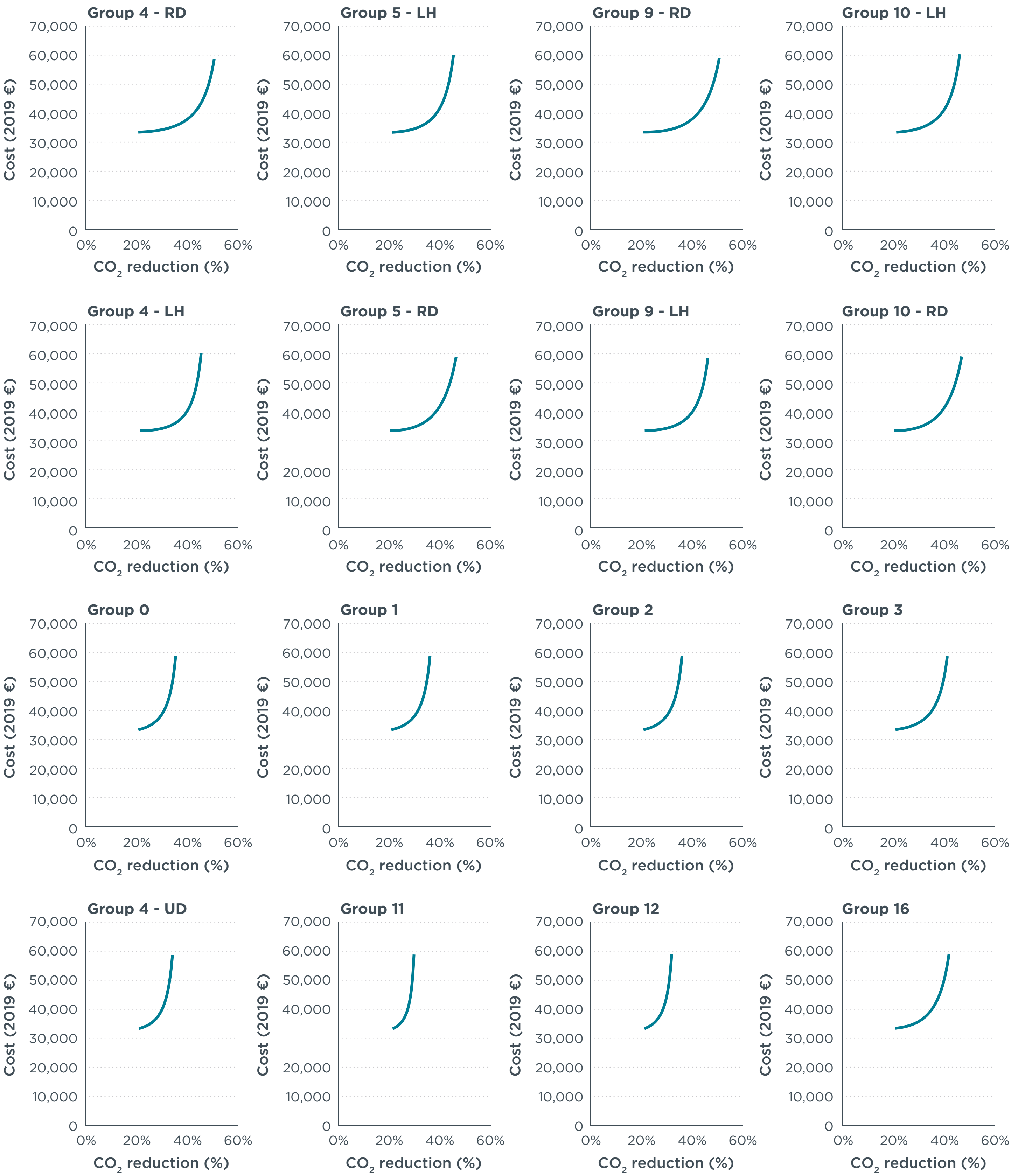

Figure 5. CO_2 technology cost curves for LNG trucks in 2030

TRUCK ZERO-EMISSION TECHNOLOGIES: BATTERY AND FUEL-CELL ELECTRIC

The tailpipe CO_2 reduction of ZE-HDV technologies is 100% when compared to diesel or LNG engines. Within the scope of this study, battery-electric trucks (BET) and fuel-cell electric trucks (FCET) are defined as ZE-HDV technologies. The truck's technical specifications highly drive the costs of BET and FCET technologies, such as its battery size, fuel cell unit power, hydrogen storage tank, electric drive rated power, and other design parameters. These technical specifications differ from one truck group to the other and within the same truck group across different truck mission profiles. In this section, we present the direct manufacturing costs of the considered ZE truck groups using a detailed cost breakdown analysis as shown in Basma, Saboori, and Rodríguez (2021) and Basma, Zhou, and Rodríguez (2022).

Since the battery and hydrogen storage tank sizes depend on the daily driving range of each truck, we assume the following average daily driving ranges per truck group, as shown in Figure 6 based on European Commission (2019b).

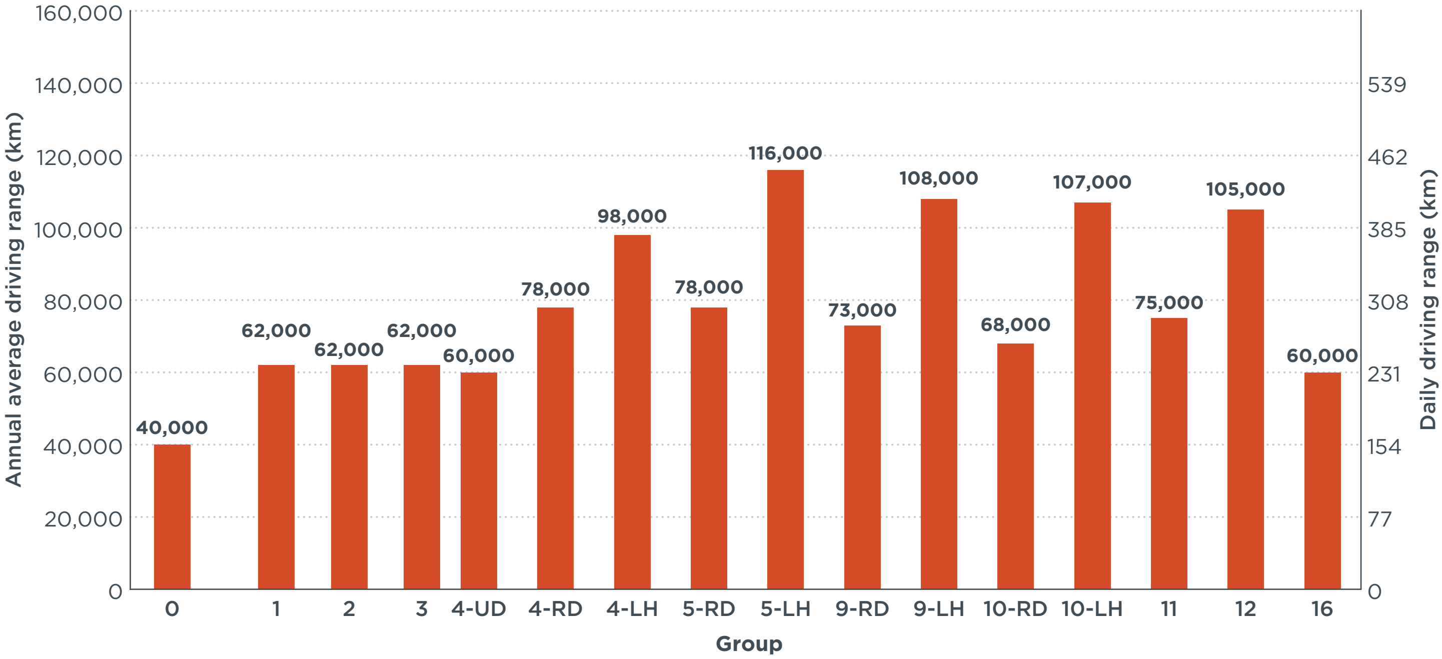

Figure 6. Average annual and daily driving range per truck group

For trucks operating long-haul, daily driving ranges could reach 1,000 km in some cases, which would significantly impact the truck battery or hydrogen tank size and, consequently, the truck's direct manufacturing cost. Thus, truck groups 4, 5, 9, and 10 that operate in long-haul are further segmented into three sub-groups based on their daily driving range: 500 km, 800 km, and 1,000 km. Wentzel (2020) provides data for the truck average daily distance for European-representative fleets, where 70% of the trucks travel less than 500 km during the day, and 97% of the trucks travel less than 800 km during the day, as shown in Figure 7. It is assumed that all trucks that travel more than 500 km, representing ~30% of trucks in the EU, according to Wentzel (2020), belong to groups 4, 5, 9, and 10 in the long-haul. Table 2 summarizes the share of the VECTO long-haul sub-groups segmented according to their daily driving ranges.

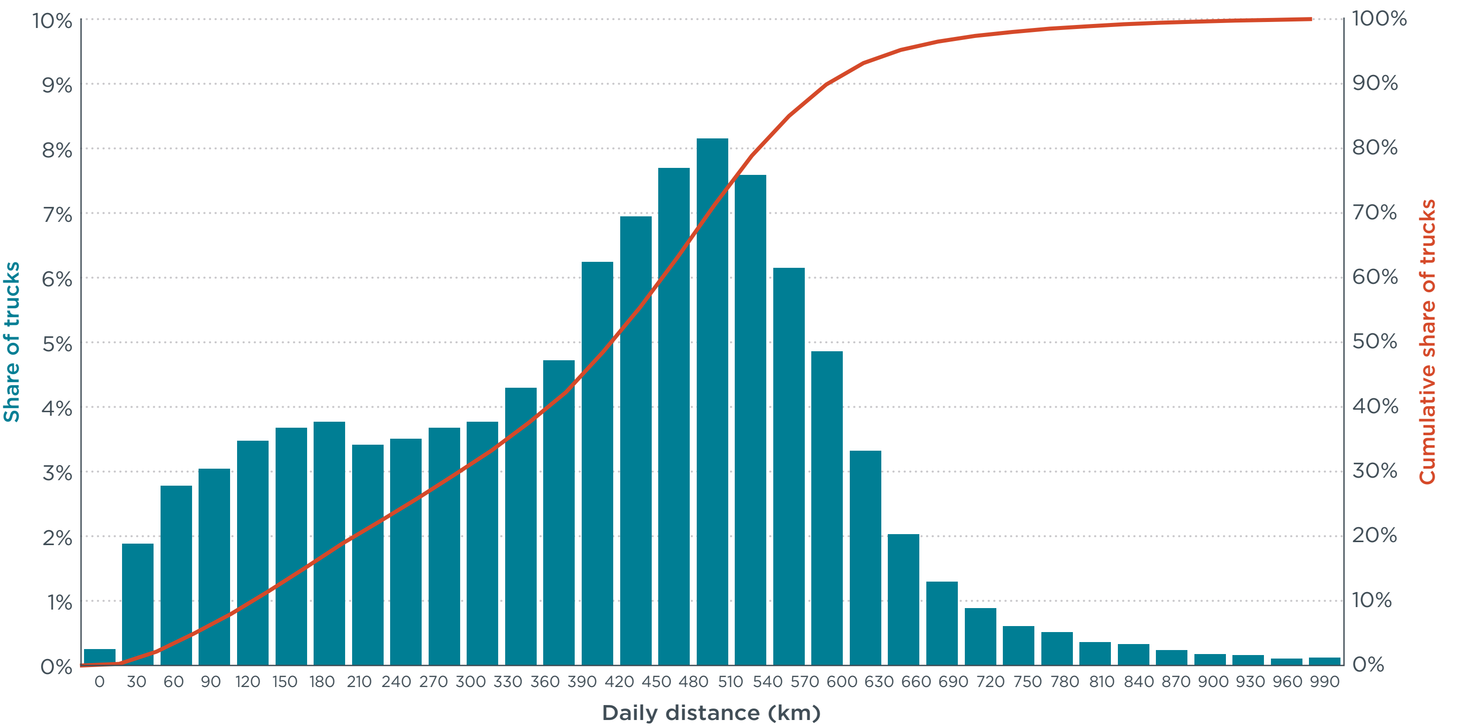

Figure 7. Average truck daily distance from a representative fleet adapted from Wentzel (2020).

Table 2. Long-haul sub-groups share segmentation based on the daily driving range

VECTO long-haul subgroups	< 500 km	500–800 km	> 800 km	Total
4-LH	1.92%	1%	0.11%	3.02%
5-LH	38.57%	20.09%	2.23%	60.89%
9-LH	6.34%	3.3%	0.37%	10.01%
10-LH	1.91%	0.99%	0.11%	3.01%
Total	48.74%	25.38%	2.82%	76.94%

For each BET group, the required battery size is estimated as a function of the truck's energy consumption and daily driving range. The truck energy consumption is calculated using VECTO, where the VECTO xEV version allows BET energy simulation. The trucks' specifications are the same as their diesel counterparts, with the e-drive power equal to the engine power. A 2-speed transmission system is considered for all BETs instead of the 6-speed and 12-speed transmission systems used in diesel trucks. Improvements in road load technologies such as aerodynamic drag coefficient, rolling resistance coefficients, and chassis light-weighting are also considered, in addition to improvement in transmission efficiency. These improvements are documented in Basma, Beys, and Rodríguez (2021) and Basma and Rodríguez (2022).

Specifications for FCETs are also considered, similar to their BET and diesel counterparts. Regarding the fuel cell stack, it is assumed that truck groups 0–2 are equipped with a 90 kW FC stack, group 3 is equipped with a 100-kW unit, groups 4, 5, 9, and 10 that operate in long-haul are equipped with 210 kW FC stack, while all other groups (including groups 4, 5, 9, and 10 in UD and RD) are equipped with 180 kW FC stack. The reason for equipping LH groups with higher FC stack power is due to the higher speed observed during the LH drive cycle compared to the RD or UD drive cycles. In addition, all truck groups are equipped with auxiliary batteries to assist the fuel cell stack during peak accelerations. The fuel cell unit nominal power and the battery size are summarized in Table A5. The fuel cell stack power and battery size are similar to what is contained in currently available commercial and concept FCET models in Europe. Those models are described in detail in Table A4 in the appendix.

FCET technology is not currently defined in VECTO. Thus, it is impossible to simulate the FCET hydrogen fuel consumption and the required hydrogen storage tank to meet their mission profiles and daily driving range requirements. Instead, the FCET hydrogen fuel consumption is estimated based on the BET electric energy consumption for each truck group as shown in equation (1), where FC_{H2} is the hydrogen fuel consumption (kg/100km), EC_{elec} is the BET electric energy consumption (kWh/km)[3], and $\eta_{Battery}$ is the battery columbic efficiency assumed equal to 95%. $\eta_{Fuel\ cell}$ is the fuel cell average conversion efficiency over the truck mission profiles. The fuel cell efficiency is derived based on detailed vehicle simulation in a previous ICCT publication (Basma & Rodríguez, 2022) and is summarized in Table A8. LHV_{H2} is hydrogen fuel lower heating value, which is equal to 33.3 kWh/kg.

$$FC_{H2} = EC_{elec} \times \frac{\eta_{Battery}}{\eta_{Fuel\ cell}} \times \frac{1}{LHV_{H2}} \times 100 \qquad (1)$$

Finally, the trucks' energy efficiency and the required battery size and hydrogen storage tank for each truck group are summarized in Table A9 and Table A10 in the appendix based on VECTO simulations and the required daily driving range per truck group. Between 2021 and 2030, the reduction in the truck energy consumption due to chassis light weighting, battery energy density improvement, and road load technologies improvement are considered as the required truck battery or hydrogen tank sizes decrease between 2021 and 2030 for a fixed daily driving range. The batteries and hydrogen tanks are sized assuming no refueling or recharging during the day. Between 2030 and 2040, FCETs are expected to realize a further improvement in energy efficiency, while no further improvement is considered for BETs.

After determining the technical specifications for each truck group and sub-group, the truck's direct manufacturing costs can be estimated. Basma, Saboori, and Rodríguez (2021) and Basma, Zhou, and Rodríguez (2022) present an in-depth, bottom-up approach to estimate the direct manufacturing cost and retail price of BETs and FCETs between 2022 and 2040 as a function of the truck technical specifications. Figure 8 and Figure 9 show the battery-electric and fuel-cell electric trucks' direct manufacturing costs for model years 2022, 2030, and 2040 for all VECTO groups and subgroups. Table A17 in the appendix summarizes the considered direct manufacturing costs of the main powertrain components for zero-emission trucks between 2022 and 2040.

3 For the same payload, the battery weight of the BET is subtracted from the GVW, while the FC stack and hydrogen storage tank weights are added.

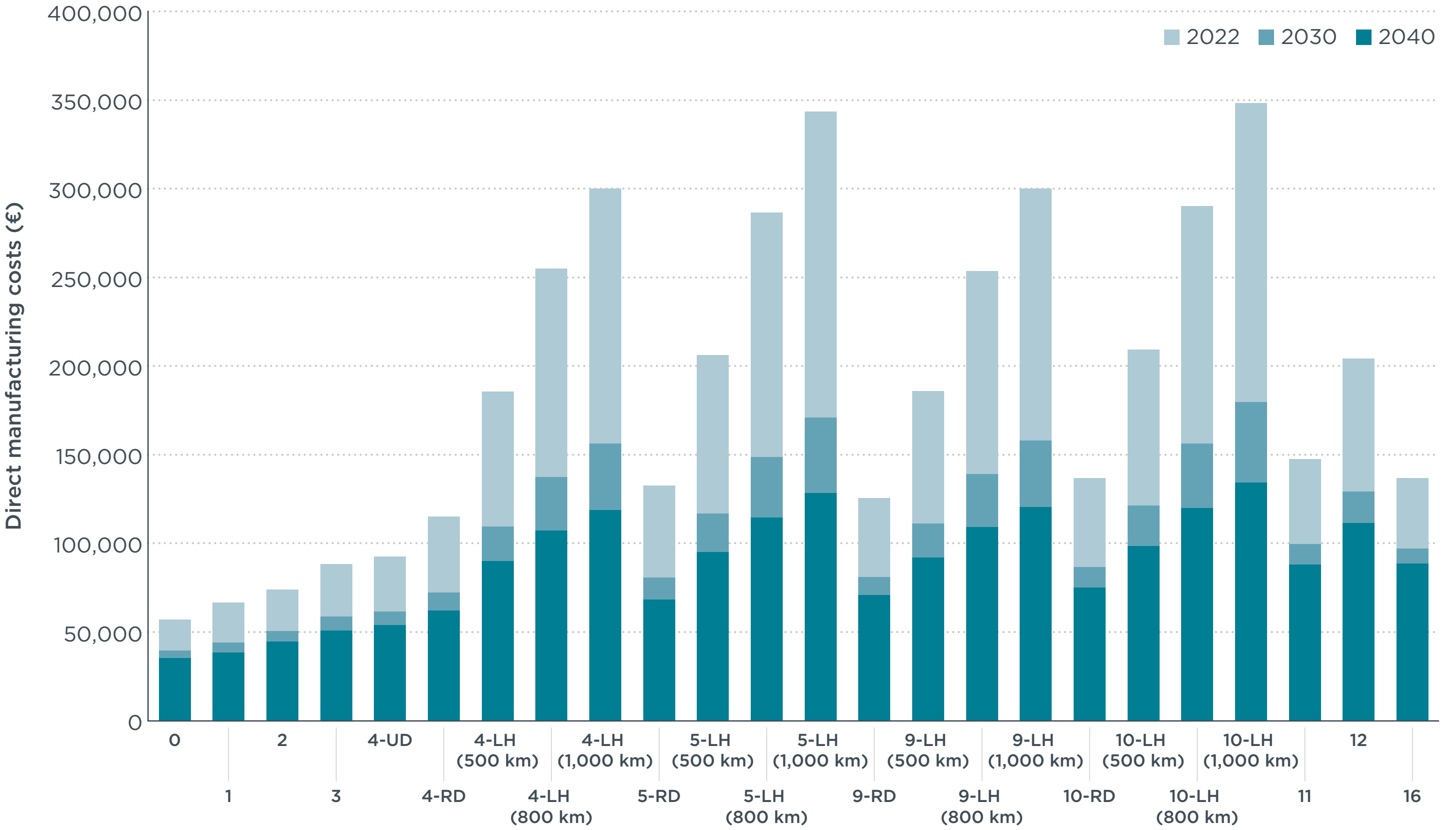

Figure 8. Battery-electric trucks' direct manufacturing costs evolution between 2022 and 2040.

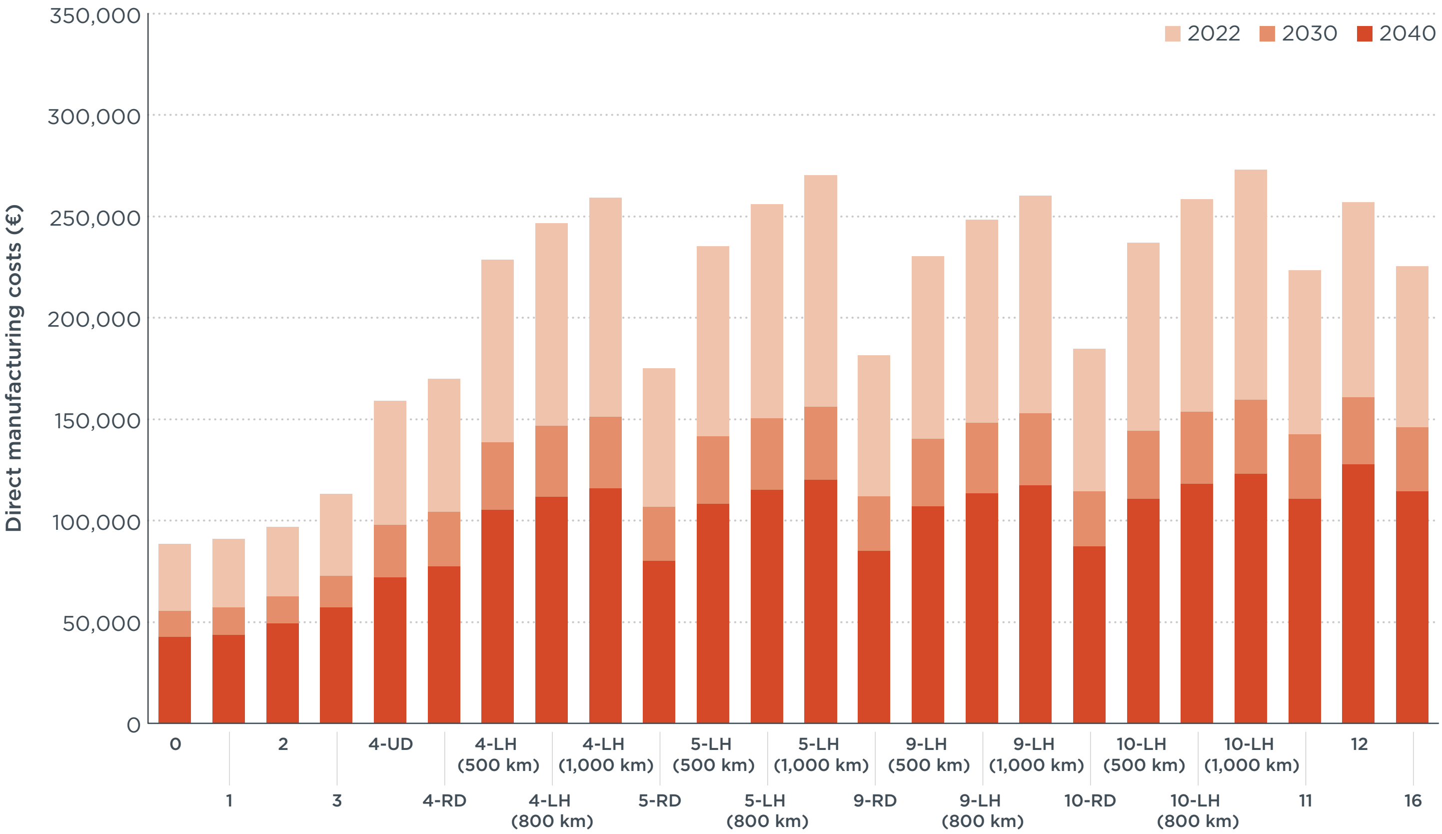

Figure 9. Fuel cell electric trucks' direct manufacturing costs evolution between 2022 and 2040.

The ZE truck's additional direct manufacturing costs are then estimated as the difference between their direct manufacturing costs and the direct manufacturing costs of an equivalent diesel truck in 2022. The additional direct manufacturing costs for BETs and FCETs are summarized in Figure 10 and Figure 11, and the retail prices and direct manufacturing costs for diesel trucks in 2022 are summarized in the appendix in Table A15.

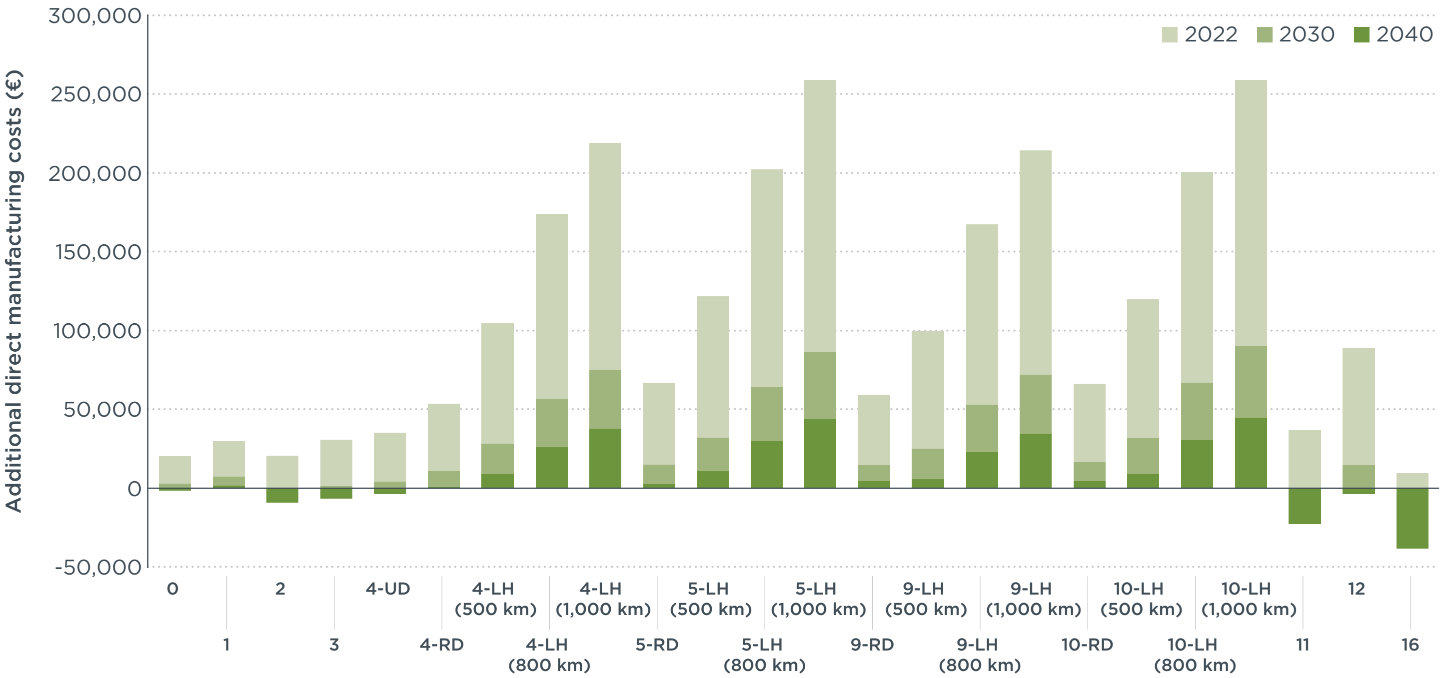

Figure 10. Battery-electric trucks' additional direct manufacturing costs relative to an equivalent diesel truck between 2022 and 2040.

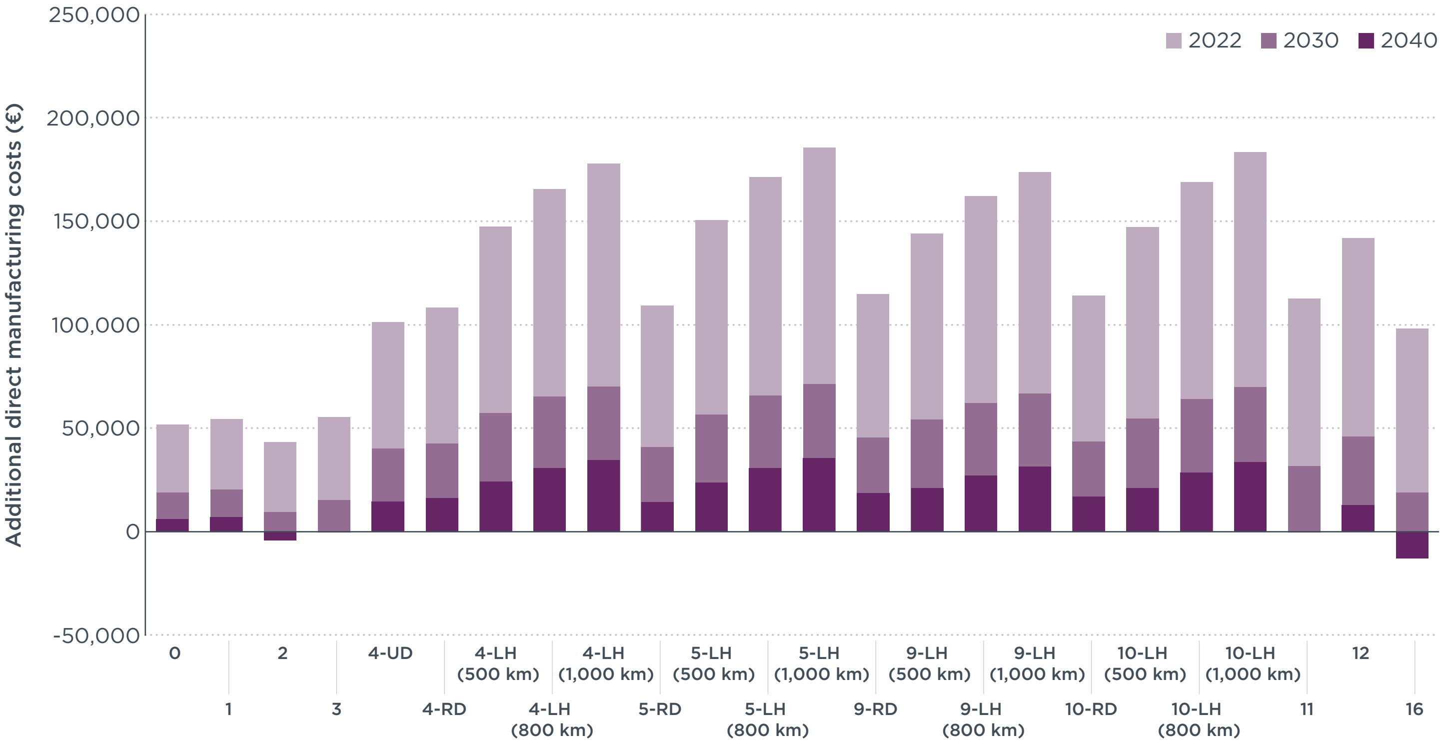

Figure 11. Fuel cell electric trucks' additional direct manufacturing costs relative to an equivalent diesel truck between 2022 and 2040

SCENARIOS FOR CO_2 REDUCTION TARGETS

The HDV fleet CO_2 cost curves are developed under two CO_2 reduction scenarios between 2030 and 2040. First, the currently adopted CO_2 reduction targets in Europe are considered under the *adopted policies* scenario. The current CO_2 standards mandate a 30% reduction in the HDV CO_2 emissions by 2030 relative to the reporting year 2019/2020. The current standards do not mention the reduction targets beyond 2030, so we assume that the 30% reduction target will remain in place until 2040 for the adopted policies scenario.

The second scenario considers the announcements made by the main HDV manufacturers in the EU, as many of them have pledged to increase the share of ZE trucks during the next two decades, reaching 100% ZE sales by 2040. We have translated these pledges into CO_2 reduction targets between 2030 and 2040. The obtained CO_2 reduction targets under this *proposed targets* scenario are a 60% CO_2 reduction by 2030, 90% by 2035, and 100% by 2040, as detailed in Mulholland et al. (2022).

Table 3 summarizes the CO_2 reduction targets between 2030 and 2040 across the two considered scenarios.

Table 3. Heavy-duty vehicles' CO_2 reduction targets under different scenarios and levels of ambition relative to the 2019/2020 reporting year.

Scenario	2030	2035	2040	Total HDV fleet emissions reduction in 2050
Adopted policies	-30%	-30%	-30%	**+8%**
Proposed targets	-60%	-90%	-100%	**-96%**

OPTIMAL TECHNOLOGY MARKET SHARE

The HDV fleet CO_2 cost curves depend on the technology market share in a given year. This section identifies the optimal technology market share to minimize the additional direct manufacturing costs to meet the HDV CO_2 reduction targets in the EU.

The cost function (f) to be minimized is the additional direct manufacturing costs. It is expressed as shown in equation (2), where $X_{i,j}$, a control variable, is the market share of technology j for VECTO group i and $ADMC_{i,j}$ is the additional direct manufacturing cost of technology j for VECTO group i. The *ADMC* in the case of ICE technologies is dependent on another control variable which is the achieved CO_2 reduction of each VECTO group and each ICE technology, based on the developed technology cost curves as presented earlier in Figure 4 and Figure 5. These control variables are referred to as Y_{DSL} and Y_{LNG}. The *ADMC* of the ZE technologies is already presented in the previous section.

$$f = min \sum_{i=0}^{N} \sum_{j=0}^{M} X_{i,j} \times ADMC_{i,j} \, (Y_{i,DSL}, Y_{i,LNG}) \qquad (2)$$

This optimization problem is constrained, where the main constraint is to achieve a certain CO_2 reduction depending on the set reduction targets. This constraint is presented in equation (3), where $CO_{2\,i,j}$ is the CO_2 emissions of technology j for VECTO group i. $CO_{2\,Baseline}$ is the baseline CO_2 emissions, and MPW_i is a factor multiplying the CO_2 emissions of each VECTO group; these are summarized in Table A18. $CO_{2_{Target}}$ is the CO_2 emissions reduction target in a given year under a certain scenario. Another constraint is imposed to respect the shares of every VECTO group as shown in equation (4) while the control variables' boundary conditions are expressed in equations (5) and (6).

$$\sum_{i=0}^{N} \sum_{j=0}^{M} X_{i,j} \times \frac{CO_{2\ i,j}\,(Y_{i,DSL}, Y_{i,LNG})}{CO_{2\ Baseline}} \times MPW_i \geq CO_{2\ Target} \tag{3}$$

$$\sum_{j=0}^{M} X_{i,j} = Share_i \,\forall\, i \in \{VECTO\ Groups\} \tag{4}$$

$$0 \leq X_{i,j} \leq Share_i \,\forall\, i \in \{VECTO\ Groups\} \cap \forall\, j \in \{Technologies\} \tag{5}$$

$$\left\{ \begin{array}{l} 0 \leq Y_{i,DSL} \leq CO_{2\ reduction_{i,DSL\text{-}max}} \\ 0 \leq Y_{i,LNG} \leq CO_{2\ reduction_{i,LNG\text{-}max}} \end{array} \forall\, i \in \{VECTO\ Groups \right\} \tag{6}$$

The presented optimization problem is solved using the Sequential Least Squares Programming (SLSQP) method, given the method's ability to deal with non-linear cost functions and inequalities in the problems' constraints.

Under the proposed CO_2 reduction scenario, a 100% reduction is mandated by 2040, which implies that only zero-emission trucks can be registered, limiting the technology options to BETs and FCETs. In this case, the cheaper technology in terms of ADMC is chosen for each VECTO group. For some VECTO groups, namely all long-haul groups with daily mileage above 500 km, accounting for more than 27% of the market, the DMC of the BET and FCET technologies are within a +/- 5% difference (see Figure 8 and Figure 9), which is considered within the study's uncertainty range. In this case, we assume that for these specific VECTO groups, either zero-emission technology can be considered the optimal technology to minimize compliance costs. The market split between BETs and FCETs for these truck segments will not be determined by their DMC, but rather by the technology's total cost of ownership, as is discussed in the cost-benefit analysis section.

Figure 12 shows the optimal technology market share to minimize the additional direct manufacturing costs to meet a certain CO_2 reduction target under the defined scenarios. Under the adopted policies scenario, the market is dominated by diesel technology at almost 80% of new registrations between 2030 and 2040, with BETs accounting for the remaining 20%. This behavior is driven by unambitious CO_2 reductions in this scenario reaching only 30% between 2030 and 2040.

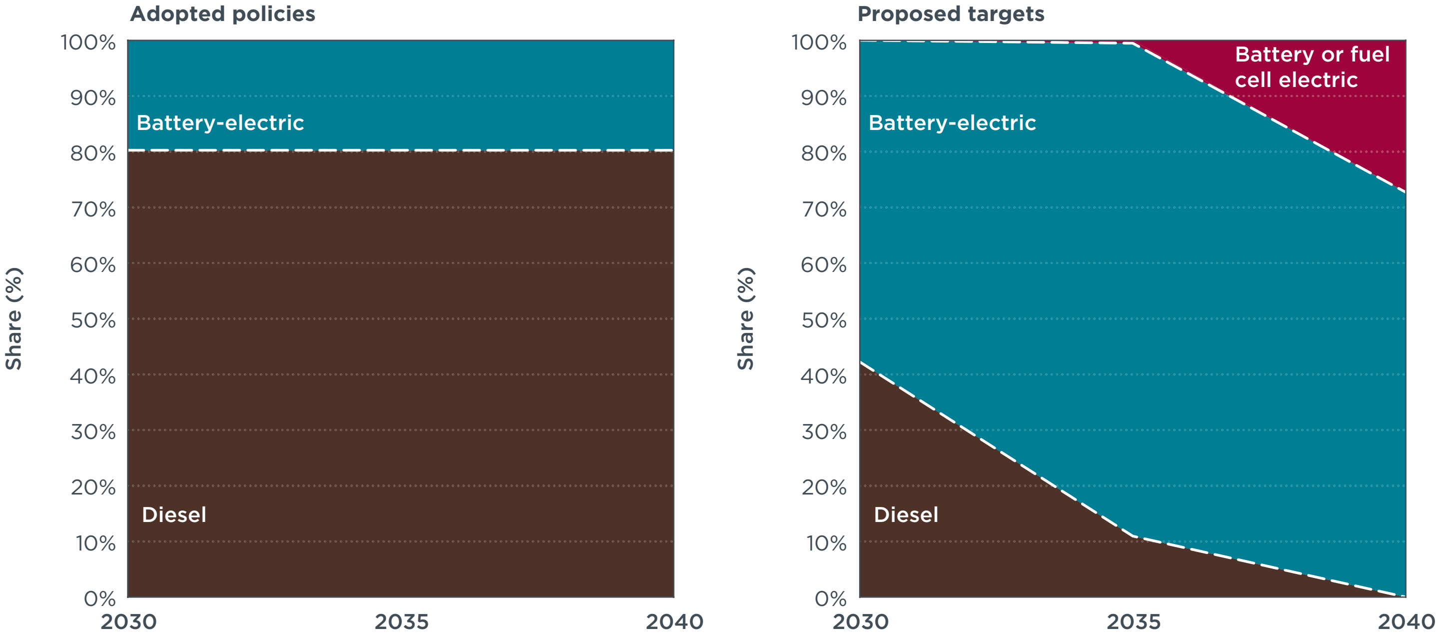

Figure 12. Optimal technology market share to minimize the additional direct manufacturing costs to meet a certain CO_2 reduction target.

Figure 13 shows the optimal technology market share per VECTO group under select CO_2 reduction scenarios. The top panel of the figure shows the optimal technology share corresponding to the 2030 adopted policies scenario. The CO_2 reduction target of 30% is met by fully electrifying all regional delivery sub-groups in addition to group 9-LH (500 km) and by improving the diesel technology by 16% to 20% for the remaining long-haul sub-groups. The electrified truck groups result in a ~16% reduction in CO_2, while the truck segments with improved diesel technologies result in a 14% CO_2 reduction, as summarized in Table 4.

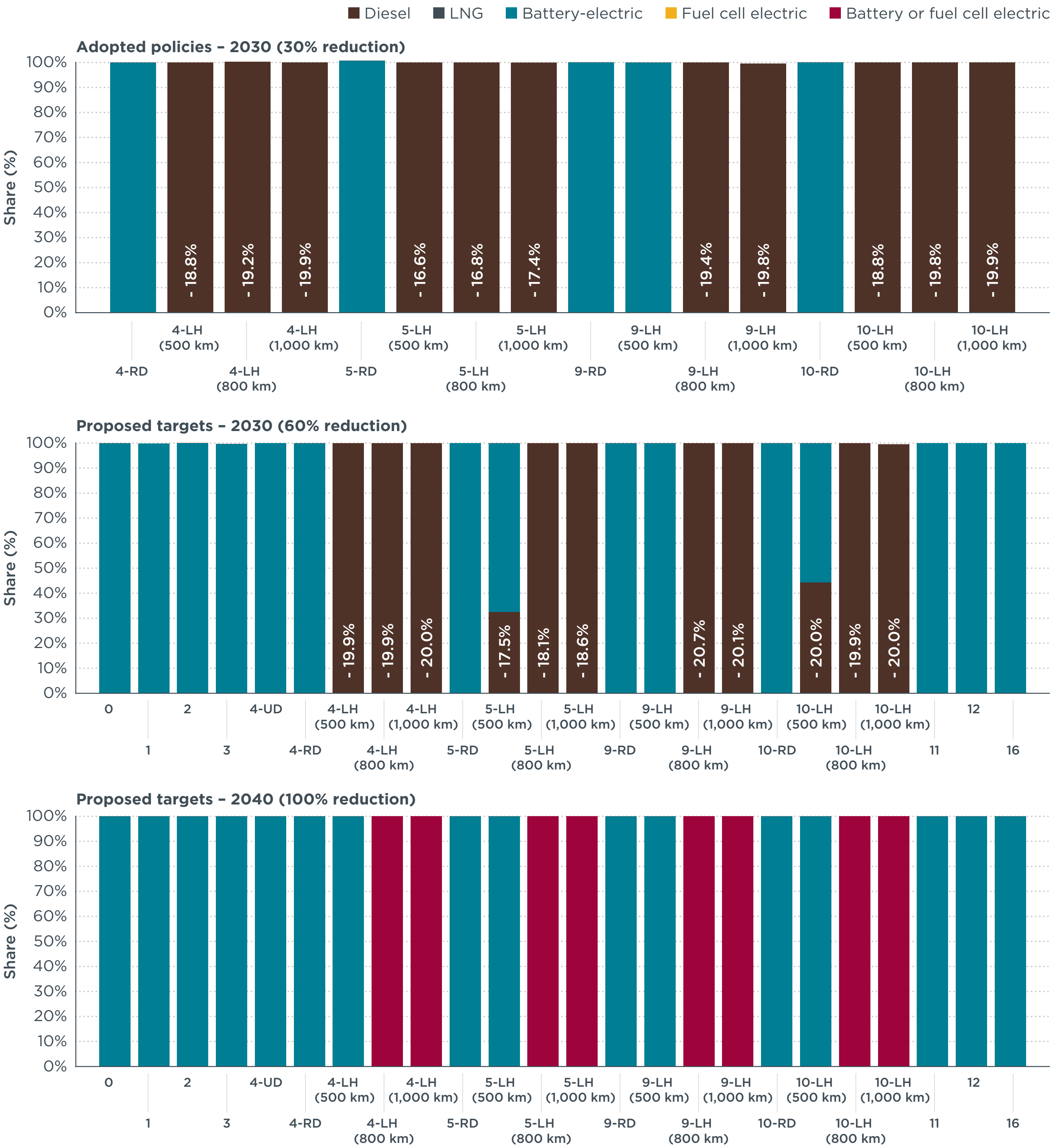

Figure 13. Optimal technology market share per VECTO group under several CO_2 reduction scenarios. Data labels on the diesel bars correspond to the technology CO_2 reduction per group.

Under the proposed targets scenario, a 60% CO_2 reduction is required by 2030, resulting in a 57% BET market share by 2030. All certified groups that don't operate in long-haul are electrified, in addition to some long haulers, to meet the reduction target, as shown in the middle panel of Figure 13. Long-haul trucks with a daily driving range of up to 500 km are first electrified to meet the CO_2 reduction target, given that they are cheaper to electrify due to the smaller battery sizes required compared to long-haul trucks with higher daily mileages. The electrified truck segments result in a ~51% reduction in CO_2, while the truck segments with improved diesel technologies result in a 9% CO_2 reduction, as summarized in Table 4.

Table 4. Summary of the optimal technologies market share and their contribution to total CO_2 reduction under the different considered scenarios.

Scenario	CO_2 reduction target (%)	Technology market share			Technology contribution to CO_2 reduction		
		DSL	BET	BET/FCT	DSL	BET	BET/FCT
Adopted policies	**30% (2030-2040)**	80%	20%	0%	14%	16%	0%
Proposed targets	**60% (2030)**	43%	57%	0%	9%	51%	0%
	90% (2035)	11%	89%	0%	3%	87%	0%
	100% (2040)	0%	73%	27%	0%	83%	17%

By 2040, the proposed targets scenario requires a 100% CO_2 reduction, implying that only ZE emission technologies are allowed. Under this scenario, BETs dominate the market with more than 73% market share. The rest of the market will also be zero-emission trucks, either BETs or FCETs. As shown in the bottom panel of Figure 13, BETs are the preferred technology for all trucks except those operating in long-haul with daily mileages above 500 km. For those trucks, the DMC of BETs and FCETs are similar, and there is no preferred technology from the manufacturers' perspective. The market split between BETs and FCETs will mainly be determined by the technology's total cost of ownership, as will be discussed in the consumer perspective section. It is worth mentioning that the optimization results suggest there will be no market for LNG trucks under any of the considered scenarios due to the technology's limited and expensive CO_2 reduction improvement relative to diesel technologies.

HDV FLEET CO_2 COST CURVES

Figure 14 presents the HDV fleet CO_2 cost curves, showing the average additional direct manufacturing cost per vehicle, also referred to as the compliance cost, as a function of registration year for the two considered scenarios in this study. The data labels correspond to the CO_2 reduction target in a given year. In general, the CO_2 reduction ambition increases with time, resulting in higher costs due to the higher required share of more expensive alternative technologies. The cost curves peak in 2030 or 2035, depending on the reduction targets, and decline onwards due to the expected reduction in the ZE technologies costs, mainly due to battery and fuel cell stack costs.

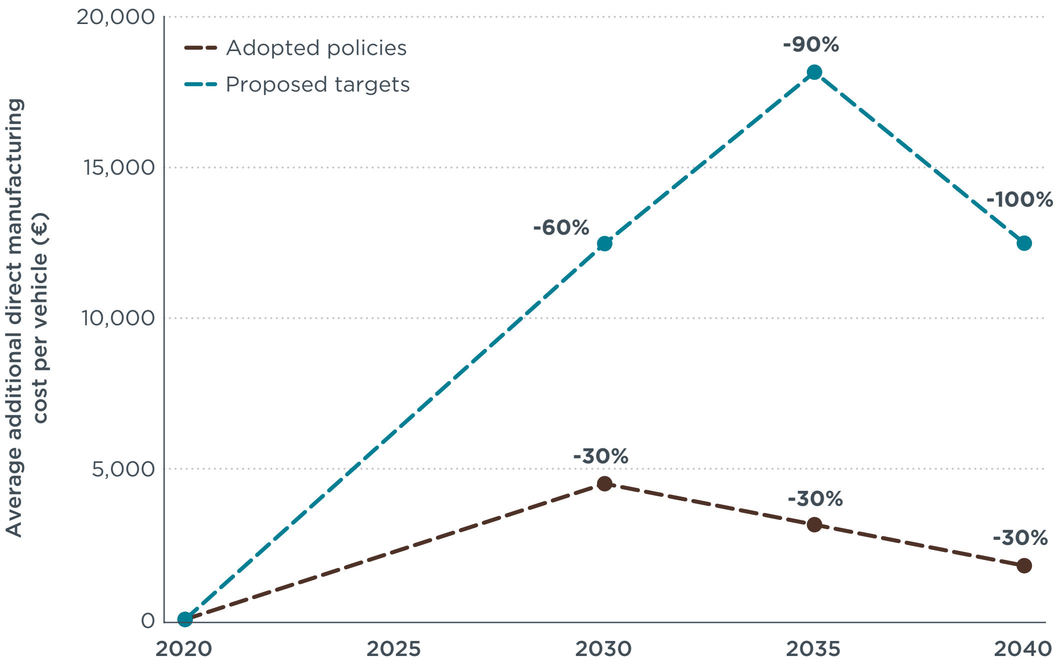

Figure 14. The average additional direct manufacturing cost per vehicle as a function of the registration year. Data labels correspond to the CO_2 reduction target in a given year.

Under the adopted policies scenario, the cost of meeting the 2030 30% CO_2 reduction target is €4,505 per vehicle, decreasing to €1,784 per vehicle by 2040 to meet the same target. This behavior is mainly driven by the reduction in the battery price, falling from €90/kWh in 2030 to €55/kWh by 2040. The average compliance cost per vehicle increases significantly under the proposed targets due to the higher CO_2 reduction ambition. The higher proposed CO_2 reduction target of 60% by 2030 results in a higher compliance cost of €12,473 per vehicle, mainly driven by the higher level of electrification needed to meet such targets. By 2035, the compliance cost curve peaks at €18,163 per vehicle to meet the 90% CO_2 reduction target. By 2040, this decreases to €12,487 per vehicle to meet the 100% CO_2 reduction target, driven by the reduction in battery prices.

Figure 15 shows HDV fleet CO_2 cost curves, illustrating the average additional direct manufacturing cost as a function of the average CO_2 reduction per vehicle for the two considered scenarios in this study.

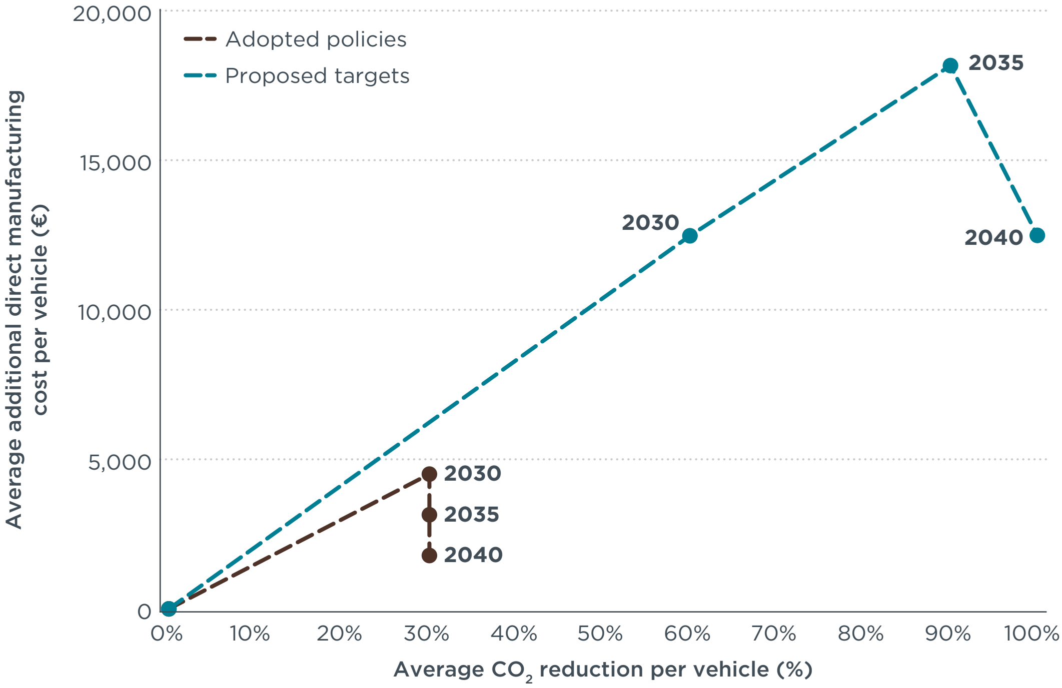

Figure 15. The average additional direct manufacturing cost per vehicle as a function of the average CO_2 reduction per vehicle. Data labels correspond to the registration year.

It is worth mentioning that the model has been validated by simulating the manufacturer's compliance costs under the scenarios proposed in the European Commission's impact assessment study to develop the current CO_2 standards for HDVs in 2018 (European Commission, 2018). The model showed an average error below 0.5%.

In addition, the mentioned impact assessment study estimated the manufacturers' compliance cost to meet the 2030 30% CO_2 reduction targets to be €19,291 per vehicle (Base cost assumptions – TL30 scenario). This is significantly higher than the estimated cost in this study of €4,505 per vehicle for the same scenario. One of the main reasons for this difference is that LNG truck technologies were assumed to represent 18.3% of new registrations by 2030 under the TL30 scenario in the impact assessment study. Because LNG truck technologies provide expensive and limited CO_2 reduction relative to diesel trucks, significant improvements in diesel technologies are required to meet the CO_2 reduction targets, which is a costly option. In this study, we propose electrifying most regional delivery trucks (see Figure 13), which provides significant CO_2 reduction at a low compliance cost. This also reduces the need to significantly improve the diesel technology, which reduces the total compliance cost.

HDV GROUPS OPTIMAL CO_2 COST CURVES

In this section, the individual cost curve of each VECTO group is optimized as opposed to the previous section, where a fleet-wide cross-optimization was conducted. This individual group optimization provides direct insights into the optimal decarbonization pathway for a specific VECTO group. Figure 16 shows the optimal CO_2 cost curve for selected VECTO groups. Analyzing VECTO group 5-LH (500km), the optimal decarbonization pathway for this group suggests limiting the diesel technology improvement until ~18% CO_2 reduction is achieved relative to the baseline by 2030. From that point onwards, more stringent CO_2 reduction targets can be met more cost-effectively by increasing the shares of zero-emission technologies, namely battery-electric. This behavior is related to the marginal cost of reducing the truck's CO_2 emissions by one additional percentage point (1% improvement).

VECTO group 5-LH (800km) shows similar behavior, but the optimal decarbonization pathway for this group suggests improving the diesel technology until ~25% CO_2 reduction is achieved relative to the baseline by 2030 since the cost of the battery-electric technology for this group is much higher than that of group 5-LH (500km). The cost curves peak at 90% CO_2 reduction targets achieved in 2035 and decline onwards, driven by the reduction in zero-emission technology costs.

All other presented groups show similar behavior but with different targets for the diesel technology CO_2 reduction. All regional delivery groups realize a much lower improvement in the diesel technology, ~10%–15%, given the more cost-effective battery-electric technologies.

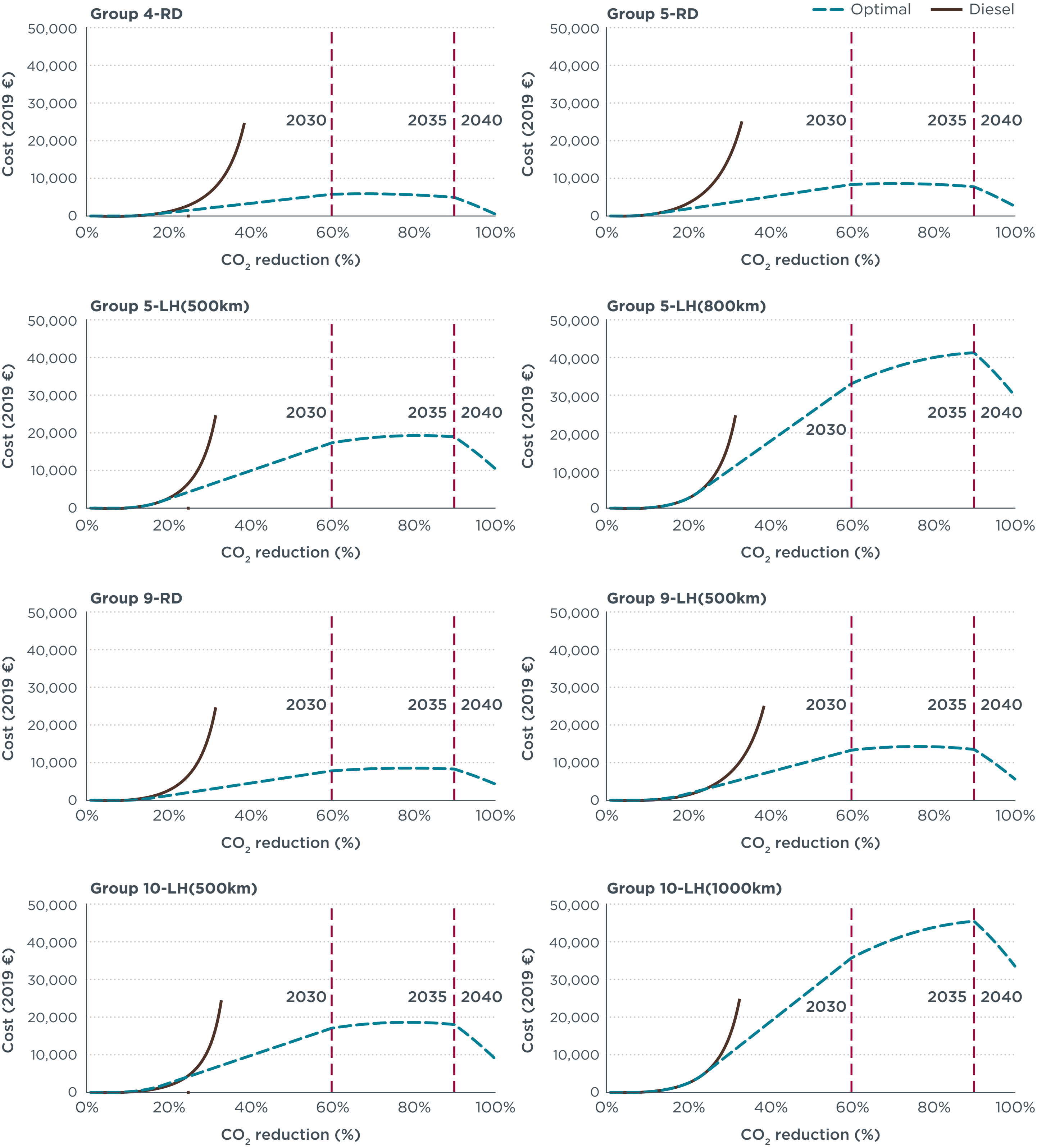

Figure 16. Optimal CO_2 cost curve for selected VECTO groups.

COST-BENEFIT ANALYSIS

The cost-benefit analysis is conducted from three perspectives: first user, second user, and societal. The first and second users' cost-benefit analyses are presented in the consumer perspective section. Table 5 shows a summary of the main inputs and assumptions used to calculate the cost benefits from the consumer and societal perspectives.

Table 5. Summary of inputs and assumptions used to quantify the cost benefits

Parameter	First ownership analysis	Second ownership analysis	Societal analysis
Analysis period	5 years	10 years	15 years
Residual value	Yes	Yes	Yes
Discount rate	9.5%	9.5%	4%
Interest rate	2%	2%	0%
Taxes	Only non-recoverable taxes considered	Only non-recoverable taxes considered	Excluded
VAT	Excluded	Excluded	Excluded
Road tolls	Included	Included	Excluded
CO_2 external cost	Excluded	Excluded	Included

CONSUMER PERSPECTIVE

This section presents the consumer cost-benefit analysis given the different CO_2 reduction scenarios presented earlier and their corresponding technology market shares. The analysis is carried out by estimating the total cost of ownership (TCO) for each VECTO group and each truck technology. The TCO methodology is well documented in several previous ICCT studies (Basma, Saboori, et al., 2021; Basma, Rodríguez, et al., 2022; Basma, Zhou, et al., 2022; Mao et al., 2021). The main components of the TCO analysis are the truck's retail price, fuel and energy cost, maintenance costs, and residual value. All these costs are converted into cash flows over the financial analysis period.

The trucks' retail price is estimated based on the calculated DMC presented earlier. The adjusted retail price of an improved ICE truck technology considers the additional direct manufacturing costs as a function of the CO_2 reduction presented in the technology cost curves.

The truck residual value is also considered using an analytical approach similar to Basma, Saboori, et al. (2021) and Basma, Zhou, et al. (2022). This results in a 46% truck residual value after the first use. The residual value of the electric components, namely the battery, fuel cell, and hydrogen tanks, are estimated separately. We assume that for the analysis period between 2030 and 2040, there will be no need for a battery, fuel cell, or hydrogen tank replacement. We assume the battery will depreciate following an Arrhenius-like behavior depending on its aging mechanisms[4]. This results in a 13% loss of battery capacity at the end of the first ownership period and a 20% loss at the end of the second ownership period, triggering the battery end-life (Basma, Haddad, et al., 2022). This yields a 43% battery residual value after the first use and 15% after the second use. For the fuel cell and hydrogen tanks, we assume they will depreciate linearly until their end of life. All residual values are summarized in Table A19 in the appendix.

4 This is a common approach for battery aging mechanisms in buses (Basma, Haddad, et al., 2022; Houbbadi et al., 2019)

The trucks' fuel and energy costs are calculated based on the trucks' fuel economy/energy efficiency, annual mileage, and energy/fuel prices. The fuel economy of an improved ICE truck technology considers the CO_2 reduction per truck under a certain scenario.

We assume that the trucks' annual mileage degrades overtime. The normalized truck annual mileage relative to the reference annual mileage, shown earlier in Figure 6, is presented in Figure A3 in the appendix. The annual mileage degradation profile is adopted from the EU TRACCS database (Emisia, 2013). The profile is adjusted so that the trucks travel their entire lifetime kilometers after 15 years of operation. Table 6 summarizes the trucks' average annual mileage during the first and second holding periods and the truck lifetime mileage. The vehicle lifetime mileage of a 5-LH VECTO group is around 1.4 million kilometers in Europe (Meszler et al., 2018). The lifetime mileages of the other VECTO groups are adjusted based on the ratio of their reference annual mileages to that of VECTO group 5-LH annual mileage as shown in Table 6.

Table 6. Summary of the truck average annual mileage during the first and second holding periods and the truck lifetime mileage.

Group	Reference annual mileage (km)	First-user average annual mileage, first 5 years (km)	Second-user average annual mileage, last 10 years (km)	Lifetime mileage (km)
0	40,000	44,263	26,144	482,759
1	62,000	68,608	40,524	748,276
2	62,000	68,608	40,524	748,276
3	62,000	68,608	40,524	748,276
4-UD	60,000	66,394	39,217	724,138
4-RD	78,000	86,313	50,982	941,379
4-LH	98,000	108,444	64,054	1,182,759
5-RD	78,000	86,313	50,982	941,379
5-LH	116,000	128,363	75,819	1,400,000
9-RD	73,000	80,780	47,713	881,034
9-LH	108,000	119,510	70,590	1,303,448
10-RD	68,000	75,247	44,445	820,690
10-LH	107,000	118,403	69,936	1,291,379
11	75,000	82,993	49,021	905,172
12	105,000	116,190	68,629	1,267,241
16	60,000	66,394	39,217	724,138

Grid electricity price data from 2021 are adopted from Eurostat (2022). By 2030, we assume that the renewable electricity share will increase to at least 50% in Europe, resulting in an average grid electricity price of 0.118 €/kWh. By 2050, grid electricity in Europe is assumed to be 100% renewable, with an average price of 0.073 €/kWh based on detailed renewable electricity price projection and modeling developed in a previous ICCT study (Zhou et al., 2022). In addition to the grid electricity price, overhead costs will be incurred by charging station operators. These costs depend on the investment cost and the chargers' utilization rate. We assume the charging stations' capital investment and operational expenses will result in 30% overhead fees to be added on top of grid electricity cost. This is an average value based on Basma, Saboori, et al. (2021). This results in a total charging cost of 0.153 €/kWh in 2030, which will decrease to 0.095 €/kWh by 2050.

Similarly for hydrogen fuel, we assume all hydrogen production is fossil-based today at 13.85 €/kg. By 2030, we assume a 50% share of hydrogen produced from renewable electricity (green hydrogen) with the remaining produced from natural gas with carbon capture technology (blue hydrogen). This results in a hydrogen price of 8.5 €/kg. By 2050, we assume all hydrogen will be produced through renewable electrolysis at a price of 5.9 €/kg.

The average net diesel fuel prices correspond to the 2021 EU average data adapted from Diesel Price Index (2022) before the price crunch in 2022. Due to the highly uncertain projections of diesel fuel prices until 2050, we assume a range of diesel fuel prices considering the European-average minimum and maximum prices between 2015 and 2022, resulting in a net minimum and maximum diesel prices of 0.75 €/liter and 1.5 €/liter, respectively (Diesel Price Index, 2022). Table 7 present a summary of fuel and energy costs.

Table 7. Summary of fuel and energy costs excluding VAT and recoverable taxes.

Year	2021	2030	2040	2050
Grid electricity (€/kWh)	0.127	0.118	0.095	0.073
Charging cost (€/kWh) [a)]	0.165	0.153	0.124	0.095
Hydrogen at-the-pump (€/kg) [b)]	13.85	8.5	7.3	5.9
Diesel (€/l) [c)]	[0.75, 1.05, 1.5]			

a) The charging stations' capital investment and operational expenses are assumed to add 30% on top of grid electricity cost. An average value based on (Basma, Saboori, et al., 2021) – pages 15-20.
b) EU average data adopted from (Basma, Zhou, et al., 2022).
c) (Diesel Price Index, 2022).

The other main component of the truck's operational expenses is maintenance costs. Maintenance costs data are mainly available as the average value over the first user holding period, which is typically five years. These data are summarized in Table A20 in the appendix. Maintenance costs increase with the truck's age, and we assume that the truck maintenance cost will linearly increase by a factor of five at its end of life, mainly 15 years, relative to the truck's first year of operation (Burnham et al., 2021). The truck's normalized maintenance cost relative to the average first user maintenance cost is presented in Figure A4 in the appendix as a function of the truck's lifetime.

Figure 17 summarizes the first user cost-benefit analysis under the two considered CO_2 reduction scenarios. In each scenario, the figure presents the capital expenses (CAPEX) savings, operational expenses (OPEX) savings, and total savings. These cost savings correspond to an average truck in years 2030, 2035, and 2040, considering the different VECTO groups and technology market shares relative to the baseline truck.

Under the currently adopted policies scenario, the total savings are around €40,000 in 2030, and reach €66,000 by 2035, mainly driven by the reduction in BETs costs. For the more ambitious proposed CO_2 reduction targets, the total cost savings in 2030 reach €70,000 for the 60% CO_2 reduction target and €110,000 in 2035 for the 90% CO_2 reduction target. This is driven by the high level of electrification needed to achieve such high CO_2 reduction targets. The error bar presented in the figure refers to different diesel fuel price scenarios, as explained in Table 7. Even under a very optimistic scenario of diesel fuel prices reaching 0.75 €/l, significant TCO savings can still exceed €70,000 per vehicle for the proposed 90% CO_2 reduction target in 2035.

The 100% CO_2 reduction target is presented differently, as shown Figure 17. For this scenario, only zero-emission trucks can be registered. While BETs are expected to dominate most of the HDV market due to their significantly lower DMC relative to FCETs, all long-haul groups with daily mileage above 500 km, accounting for more than 27% of the market, can be decarbonized with either battery-electric or fuel cell technology, as their DMC is very similar. We examine two scenarios where those long-haul groups are either BETs or FCETs. As shown in Figure 17, the BET scenario can provide up to 30%–40% more cost savings than the FCT scenario by 2040. This is mainly due to the lower energy costs of BETs driven by their higher energy efficiency relative to FCETs and by the lower renewable electricity prices compared to green hydrogen. If there are no operational constraints such as driving range, payload capacity, or recharging time limitations, BETs can provide significant TCO savings even for trucks operating in long-haul with daily driving ranges reaching 1,000 km.

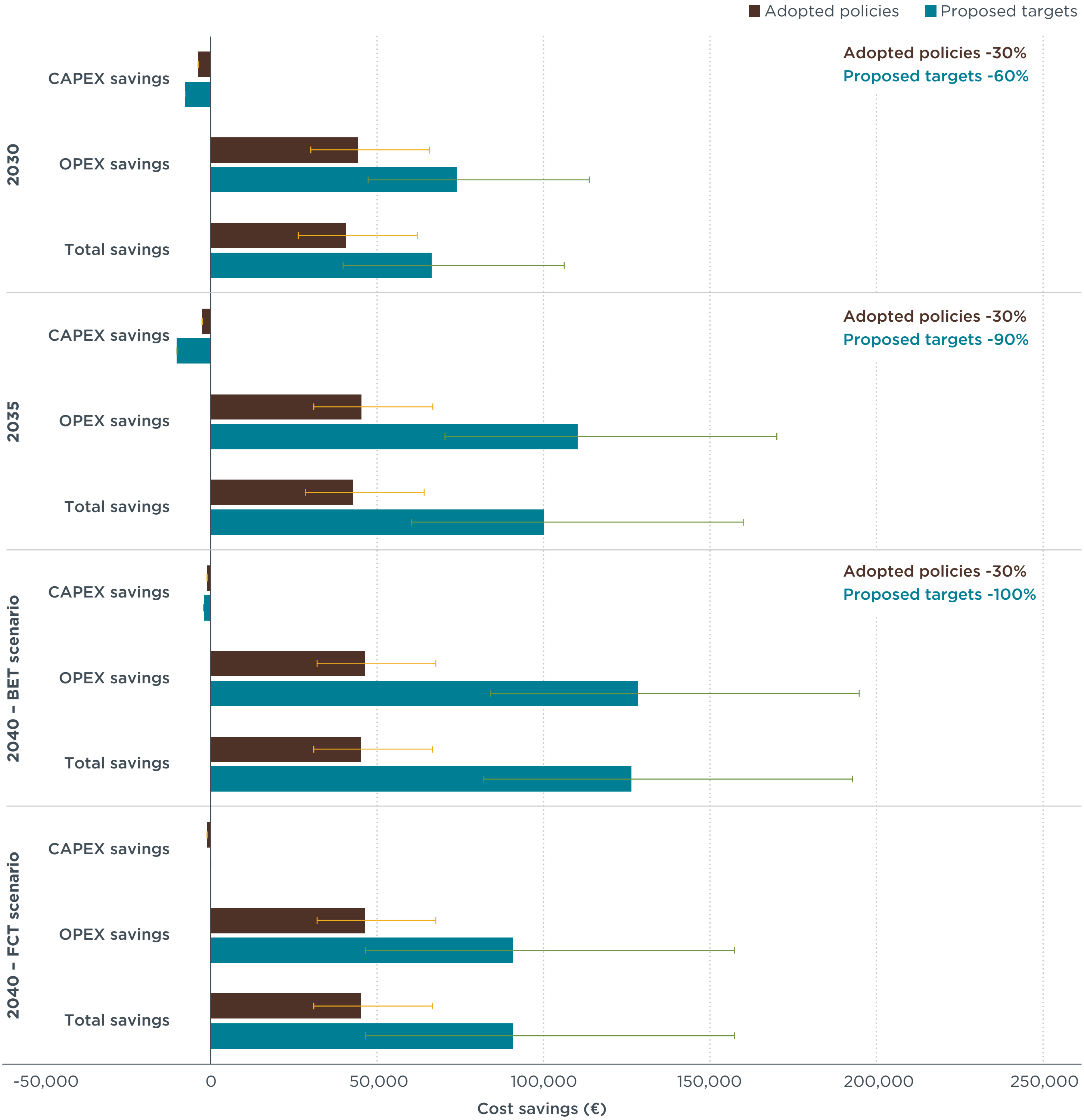

Figure 17. First user average cost savings per vehicle.

Figure 18 summarizes the second user cost-benefit analysis under the different CO_2 reduction scenarios. Similar to the cost-benefit analysis during the first use phase, the consumer can achieve significant cost savings, especially for scenarios with high CO_2 reduction ambition where BETs dominate the market. The total savings recorded during the truck's second use phase are almost 20% higher than those during its first use phase due to higher total mileage driven in the second use phase over ten years. It is worth noting that the CAPEX savings are negative in the trucks' second use phase, implying that it is more expensive to purchase a used electric truck than a used diesel truck. Nonetheless, this has a minimal impact on the total savings as the operational expenses of the truck dominate its TCO during its second use phase.

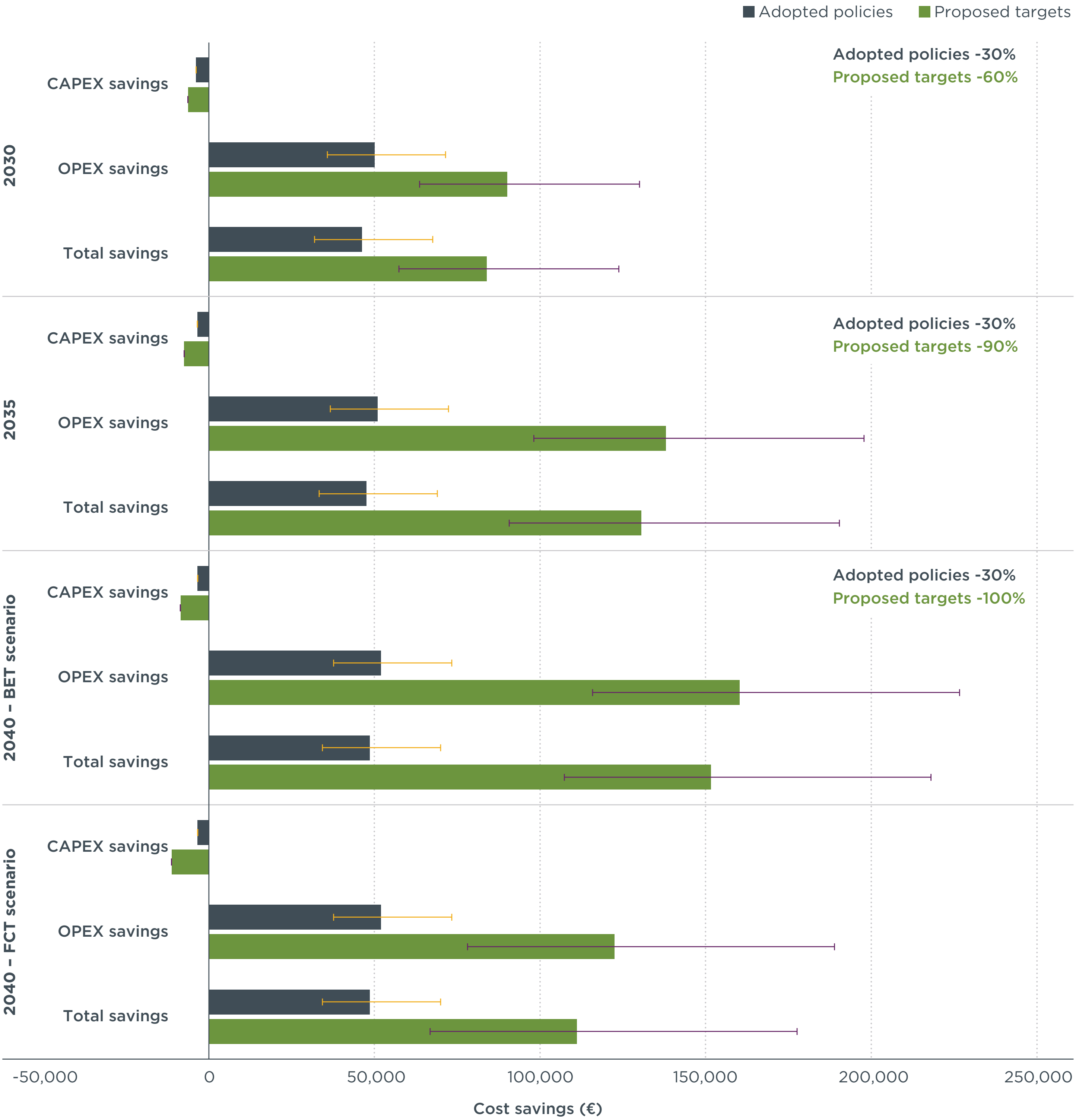

Figure 18. Second user average cost savings per vehicle.

SOCIETAL PERSPECTIVE

This study also examines the cost benefits from a societal perspective over the full-service life of the trucks, considering a 15-year analysis period, disregarding all taxes, levies, fees, and incentives, as well as considering the external cost of GHG emissions to society.

The truck life cycle GHG emissions are estimated over the vehicle and fuel cycle. GHG emissions of the vehicle cycle represent all emissions due to the truck's manufacturing. GHG emissions incurred during the fuel cycle consist of well-to-tank (WTT) and tank-to-wheel (TTW) emissions. WTT emissions include all the upstream emissions generated in various processes from extracting the primary energy all the way when it is ready for the end-user at the station. TTW emissions are the GHG emissions released due to truck energy consumption during use. In diesel trucks, fuel combustion releases the carbon content of the diesel fuel, while the TTW emissions are zero for zero-emission trucks.

It is assumed that the electricity grid's carbon intensity will decrease over time as more renewable electricity generation is integrated into the grid. The current EU-average electricity grid intensity is around 270 g CO_2e/kWh, which is assumed to decrease to ~175 g CO_2e/kWh by 2030. This drops to ~120 CO_2e/kWh by 2040 and 25.5 CO_2e/kWh by 2050, where we assume 100% renewable electricity. Hydrogen fuel WTT carbon intensity is also considered to decrease over time, assuming an increasing share of cleaner hydrogen production pathways during the next three decades. In 2022, we assume all hydrogen production is fossil-based, resulting in a carbon intensity of 13.59 kg CO_2e/kg. By 2030, we assume a 50% share of hydrogen produced from renewable electricity (green hydrogen) with the remaining produced from natural gas with carbon capture technology (blue hydrogen). This results in a hydrogen carbon intensity of 3.56 kg CO_2e/kg. By 2050, we assume all hydrogen will be produced through renewable electrolysis with a carbon intensity of 1.3 kg CO_2e/kg. More details about these assumptions can be found in O'Connell, Pavlenko, Bieker, and Searle (2023).

Table 8 shows the carbon intensities used for estimating the GHG emissions of the vehicle cycle and fuel cycle.

Table 8. Carbon intensities during the vehicle and fuel cycles.

Vehicle cycle GHG emissions intensity				
Component	**2022**	**2030**	**2040**	**2050**
Battery (kg CO_2e/kWh) [a]	58	37	37	37
Fuel-cell (kg CO_2e/kW) [b]	30	16	13	13
Hydrogen tank (kg CO_2e/kg H_2) [b]	480	330	290	290
Truck base glider (kg CO_2e/tonne) [a]	6,590			
Fuel cycle GHG emissions intensity				
Well-to-tank				
Diesel (kg CO_2e/l) [c]	0.98	0.95	0.95	0.95
Hydrogen (kg CO_2e/kg) [a]	13.59	3.56	2.44	1.3
Electricity (g CO_2e/kWh) [a]	269.7	174.3	119.9	25.5
LNG (kg CO_2e/kg) [c]	0.76			
Tank-to-wheel				
Diesel (kg CO_2e/l) [c]	2.44			
Hydrogen (kg CO_2e/kg)	0			
Electricity (g CO_2e/kWh)	0			
LNG (kg CO_2e/kg) [c]	2.71			

[a] O'Connell et al. (2023)
[b] Sternberg et al. (2019)
[c] Bieker (2021)

The CO_2 external costs to society are estimated as a function of the truck technology CO_2 emissions and the CO_2 emissions avoidance cost defined in European Commission, (2019a). The CO_2 avoidance cost is considered to be 100 €/tonne CO_{2e} between 2022 and 2030; it will then linearly increase to 269 €/tonne CO_{2e} by 2040 and remains at this level until 2055, as reported in European Commission (2019a).

Figure 19 shows the average life cycle GHG emissions savings per vehicle over the vehicle lifetime between 2030 and 2040 under the two considered CO_2 reduction scenarios. In 2030, the more ambitious proposed 60% CO_2 reduction target can provide GHG emissions savings exceeding 600 g CO_2e/km, 1.8 times more GHG emissions savings than under the currently adopted policies. While the tail-pipe CO_2 emissions are reduced by a factor of 2 (30% to 60%) between the two considered scenarios, the life cycle GHG emissions are only 1.8 times higher, as this metric also includes the truck GHG emissions during manufacturing and the fuel GHG emissions from well-to-tank as well, which are both higher for zero-emission technologies in comparison to diesel technology. By 2040, GHG emissions savings approach 1,000 g CO_2e/km, and the difference between the BET and FCT scenario is negligible. Although the fuel cycle GHG emissions of the BET scenario are lower, the vehicle cycle GHG emissions are much higher, driven by the significant GHG emissions during battery manufacturing, especially since long-haul trucks are equipped with large batteries.

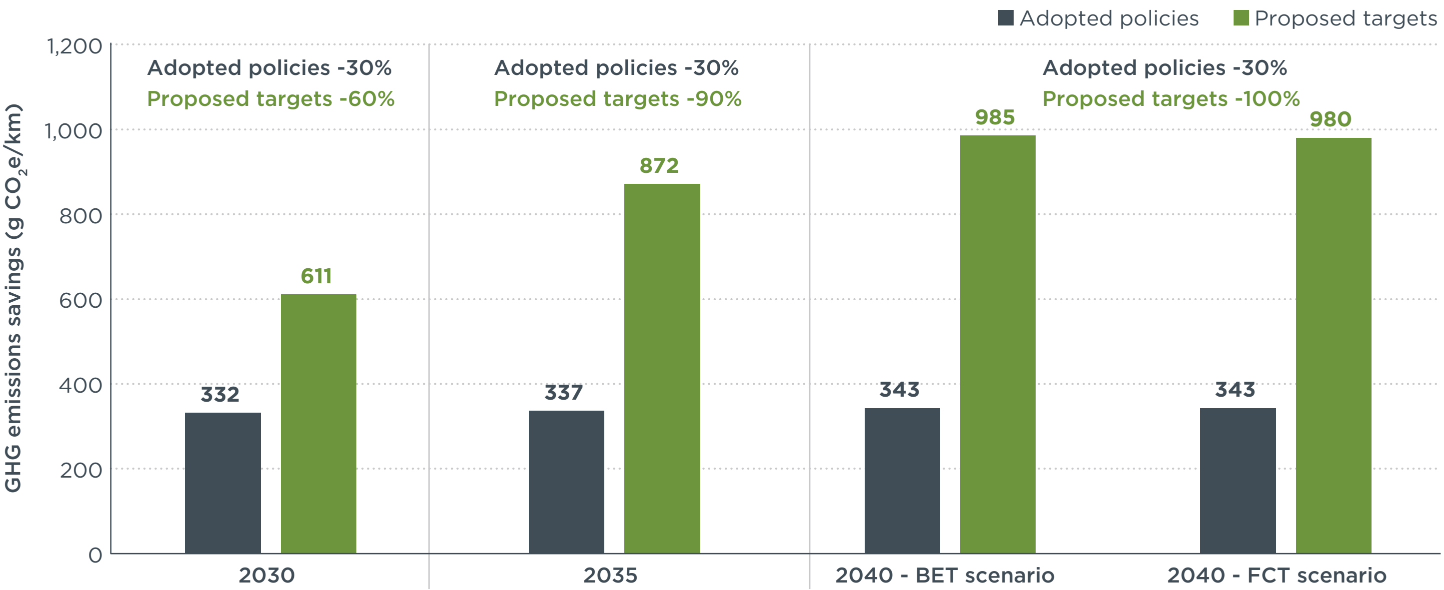

Figure 19. Average life cycle GHG emissions savings per vehicle over the vehicle lifetime.

Figure 20 shows the societal cost savings under the current CO_2 reduction targets and the proposed CO_2 reduction targets. The societal savings aggregate the cost savings from a TCO perspective and the CO_2 avoidance cost. Higher societal cost savings are obtained with more ambitious CO_2 reduction targets, exceeding €500,000 per vehicle over its lifetime for the 100% CO_2 reduction target in 2040, almost three times higher than the societal benefits recorded under the currently adopted policies of 30% CO_2 reduction.

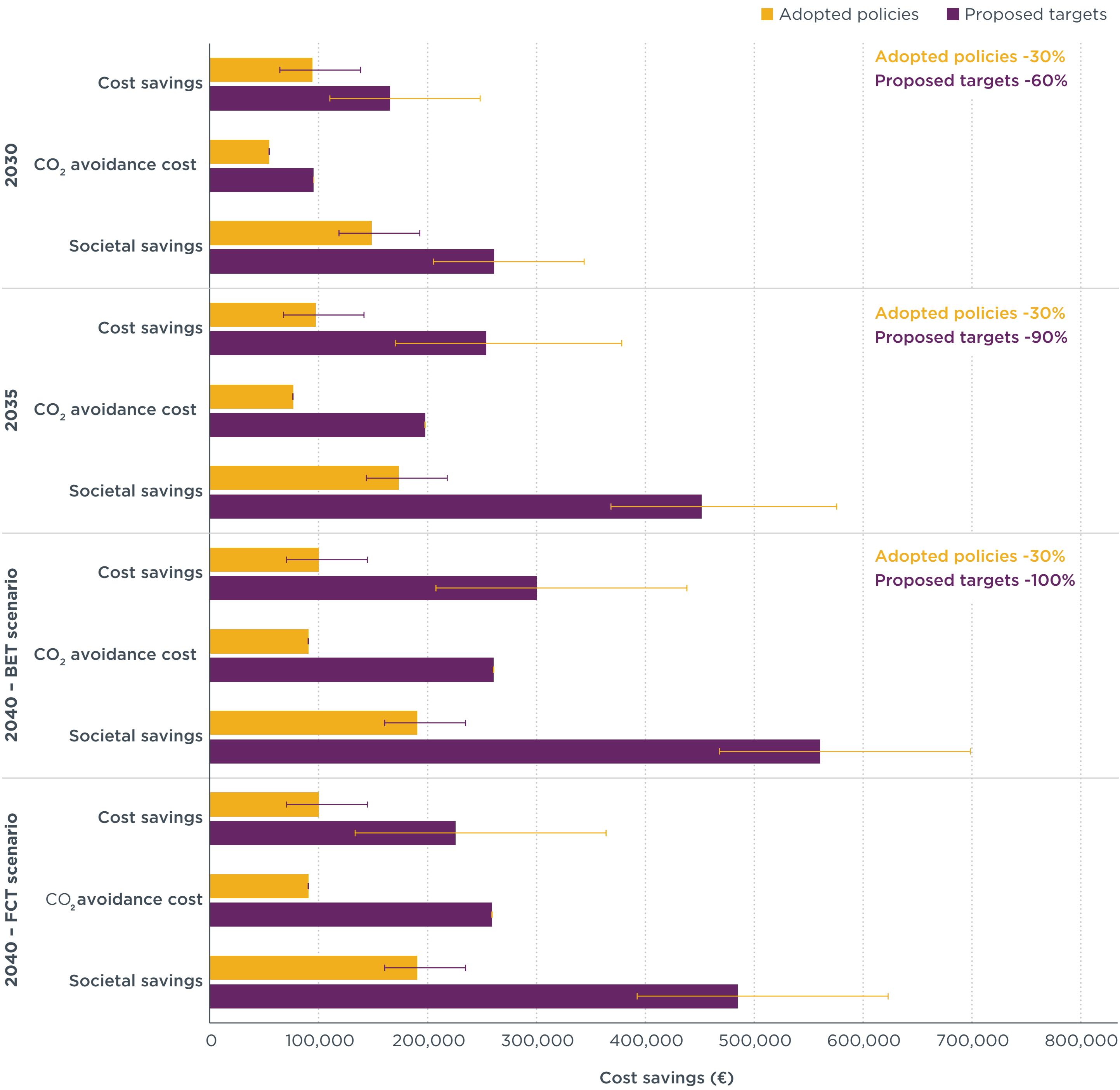

Figure 20. Societal cost savings under the current CO_2 reduction targets and the proposed CO_2 reduction targets.

CONCLUSIONS

This study examines the cost-effectiveness of the different CO_2 reduction strategies for the HDV sector between 2030 and 2040 in Europe. The study focuses on diesel, liquified natural gas, battery-electric, and hydrogen fuel-cell electric trucks. We assess the manufacturer's compliance costs and quantify the cost-benefits for consumers and society. We compare two CO_2 reduction scenarios; (1) constant 30% CO_2 reduction by 2030–2040 considering the currently adopted policies, and (2) a proposed progressive CO_2 reduction starting at 60% by 2030 and increasing to 100% by 2040, with a 90% intermediate CO_2 reduction target in 2035. We arrive at the following key findings:

» **Battery-electric trucks are expected to dominate new registrations of heavy-duty vehicles in the European market by 2040, while hydrogen fuel-cell trucks will probably play a secondary role**. BETs have the potential to provide significant CO_2 reductions at relatively low additional direct manufacturing costs. From a compliance cost perspective, it will be cheaper to electrify most truck segments than to significantly improve diesel technologies to comply with the CO_2 reduction targets. For the currently adopted policies, the 30% CO_2 reduction target can be met by electrifying most truck segments except for long-haul trucks, which account for roughly 30% of the HDV market, while improving the diesel technology by 10%–15% for long-haul trucks would be enough to comply with this target.

  Under the proposed high-ambition scenario, the cost-optimal technology market share to meet the 60% CO_2 reduction target by 2030 involes transitioning to battery-electric technologies for most truck segments, including long-haul trucks with daily driving mileages up to 500 km. Long-haul trucks with daily mileages above 500 km will be expensive to electrify by 2030 and will still rely on improved diesel technologies.

  By 2040, the 100% CO_2 reduction target allows only registrations of zero-emission trucks, i.e., battery-electric and hydrogen fuel-cell technologies. From a compliance cost perspective, battery electric will be the cheaper technology for most truck segments, including long-haul trucks with driving mileages up to 500 km. For long-haul trucks with driving mileages above 500 km, the manufacturing costs of both zero-emission technologies will be very similar. However, the consumer and societal cost-savings will be at least 30% higher if these long-haul trucks are decarbonized using battery-electric technologies, mainly due to the higher operating expenses of fuel-cell trucks, driven by the price of hydrogen fuel and their lower energy efficiency relative to their battery-electric counterparts.

» **More significant investments are required to meet the needed CO_2 reduction ambition between 2030 and 2040**. Considering the currently adopted policies, the compliance cost of meeting the 2030 30% CO_2 reduction target is €4,505 per vehicle, decreasing to only €1784 per vehicle by 2040. The average compliance cost per vehicle increases for the higher proposed CO_2 reduction targets. The 60% proposed CO_2 reduction target by 2030 will result in a €12,473 per vehicle compliance cost. The compliance cost peaks in 2035 to meet the 90% proposed CO_2 reduction target at €18,163 per vehicle. By 2040, this decreases to €12,487 per vehicle to meet the 100% CO_2 reduction target driven by the expected reduction in battery prices.

» **The most cost-effective decarbonization pathway entails a gradual shift towards truck electrification as of 2030 without fully exploiting the CO_2 reduction potential of diesel trucks.** More stringent CO_2 reduction targets can be met by either improving the diesel technology or by increasing the shares of zero-emission technologies. For the case of long-haul tractor-trailers, this segment's most cost-effective decarbonization pathway includes improving the diesel technology up to a ~18% reduction in CO_2—instead of fully exploiting the ~ 30% CO_2 reduction potential—relative to the baseline by 2030. Afterward, more stringent CO_2 reduction targets can be met by gradually increasing the share of battery-electric trucks until full decarbonization is reached by 2040.

» **Higher CO_2 reduction targets will provide significant cost savings for the consume**r. The trucks' first and second users will record higher cost savings under the high CO_2 reduction scenario compared to the currently adopted low-ambition policies. By 2030, the high-ambition 60% CO_2 reduction target can provide average costs savings of €35,000 to €110,000 per vehicle for the user depending on the diesel fuel prices, which is significantly higher than the €25,000 to €60,000 per vehicle savings under the currently adopted policies. By 2040, a 100% CO_2 reduction target can provide average cost savings of €80,000 to €180,000 per vehicle for the user, depending on diesel fuel prices. The higher investment costs are countered by more efficient and cheaper operation for battery-electric technologies.

» **More ambitious CO_2 reduction targets can significantly reduce GHG emissions and provide higher societal cost savings.** In 2030, the 60% proposed CO_2 reduction target results in ~600 g CO_2e/km GHG emissions savings, which is 1.8 times higher than what can be achieved under the currently adopted policies. By 2040, the 100% CO_2 reduction target can result in ~1,000 g CO_2e/km GHG emissions savings. In addition to the significant cost savings from a total cost of ownership perspective over the vehicle lifetime, the CO_2 avoidance cost to society further increases the societal cost savings under more ambitious CO_2 reduction targets. The proposed target can provide €450,000 to €700,000 per vehicle average societal cost savings depending on the diesel fuel prices, which is much higher than the societal cost savings that can be achieved under the currently adopted policies of €170,000 to €240,000 per vehicle.

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APPENDIX

VECTO SIMULATION PARAMETERS

Table A1. Summary of trucks technical specifications used in VECTO simulations

Group	Drag area	RRC [a)]	Curb mass	GVW	Engine power	Transmission
0	4.83 m^2	0.0065/ 0.0075	4,800 kg	7.5 tonnes	170 kW	6-speed MT
1	4.83 m^2	0.0065/ 0.0075	4,800 kg	10 tonnes	170 kW	6-speed MT
2	4.83 m^2	0.0065/ 0.0075	4,800 kg	12 tonnes	170 kW	6-speed MT
3	4.83 m^2	0.0055/ 0.0065	8,229 kg	16 tonnes	220 kW	12-speed AMT
4-UD	5.3 m^2	0.0055/ 0.0065	8,229 kg	40 tonnes	170 kW	12-speed AMT
4-RD	5.3 m^2	0.0055/ 0.0065	8,229 kg	40 tonnes	220 kW	12-speed AMT
4-LH	5.3 m^2	0.0055/ 0.0065	8,229 kg	40 tonnes	325 kW	12-speed AMT
5-RD	5.3 m^2	0.0055/ 0.0065	8,229 kg	40 tonnes	220 kW	12-speed AMT
5-LH	5.3 m^2	0.0055/ 0.0065	8,229 kg	40 tonnes	325 kW	12-speed AMT
9	5.2 m^2	0.0055	9,300 kg	40 tonnes	325 kW	12-speed AMT
10	5.2 m^2	0.0055	9,300 kg	40 tonnes	325 kW	12-speed AMT
11	5.2 m^2	0.0055	9,600 kg	40 tonnes	325 kW	12-speed AMT
12	5.2 m^2	0.0055	9,600 kg	40 tonnes	325 kW	12-speed AMT
16	5.2 m^2	0.0055	11,200 kg	40 tonnes	325 kW	12-speed AMT

[a)] Rolling resistance coefficient for multiple truck axles

Table A2. Trucks reference and low payloads per mission profile for each truck group

Payload (kg)	Long-haul		Regional delivery		Urban delivery		Municipal utility		Construction	
Group	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**
0	-	-	249	1,090	249	1,090	-	-	-	-
1	-	-	446	2,231	446	2,231	-	-	-	-
2	1,303	9,841	604	3,020	604	3,020	-	-	-	-
3	-	-	919	4,596	919	4,596	-	-	-	-
4	1,900	14,000	900	4,400	900	4,400	600	3,000	-	-
5	2,600	19,300	2,600	12,900	2,600	12,900	-	-	-	-
9	2,600	19,300	1,400	7,100	-	-	1,200	6,000	-	-
10	2,600	19,300	2,600	12,900	-	-	-	-	-	-
11	2,600	19,300	1,400	7,100	-	-	1,200	6,000	1,400	7,100
12	2,600	19,300	2,600	12,900	-	-	-	-	2,600	12,900
16	-	-	-	-	-	-	-	-	2,600	12,900

Table A3. Mission profiles weights for each truck group and sub-group

%	Long-haul		Regional delivery		Urban delivery		Municipal utility		Construction	
Group	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**	**Low**	**Ref.**
0	-	-	3%	7%	45%	45%	-	-	-	-
1	-	-	3%	7%	45%	45%	-	-	-	-
2	0%	0%	3%	7%	45%	45%	-	-	-	-
3	-	-	25%	25%	25%	25%	-	-	-	-
4- UD	0%	0%	0%	0%	50%	50%	0%	0%	-	-
4 - RD	5%	5%	45%	45%	0%	0%	0%	0%	-	-
4 - LH	45%	45%	5%	5%	0%	0%	0%	0%	-	-
5 - RD	3%	7%	27%	63%	0%	0%	-	-	-	-
5 - LH	27%	63%	3%	7%	0%	0%	-	-	-	-
9 - RD	3%	7%	27%	63%	-	-	0%	0%	-	-
9 - LH	27%	63%	3%	7%	-	-	0%	0%	-	-
10 - RD	3%	7%	27%	63%	-	-	-	-	-	-
10 - LH	27%	63%	3%	7%	-	-	-	-	-	-
11	0%	0%	0%	0%	-	-	50%	50%	0%	0%
12	3%	7%	0%	0%	-	-	-	-	27%	63%
16	-	-	-	-	-	-	-	-	30%	70%

Table A4. Summary of current commercial and concept FCET models

Model/OEM	FC power	Battery size	E-drive power	H2 tank size	H2 tank technology	Range [a)]
Hyundai-Xcient	180 kW	72 kWh	350 kW (Cont.)	31 kg	350 bars	400 km
Scania-P Series	90 kW	56 kWh	210 kW (Cont.)	33 kg	350 bars	450 km
Daimler-GenH2	300 kW	70 kWh	460 kW (Cont.)	80 kg	Liquid	1,000 km
DAF-VDL	60 kW	85 kWh	-	30 kg	350 bars	350 km
DAF-VDL	60 kW	82 kWh	-	30 kg	350 bars	400 km
MAN	100 kW	120 kWh	-	34 kg	350 bars	400 km
Freightliner	210 kW	-	-	100 kg	350 bars	700 km
Navistar	60 kW	-	-	19 kg	350 bars	-
Nikola	240 kW	250 kWh	750 kW (Max)	81 kg	700 bars	1,000 km

[a)] Average reported driving range based on OEM's announcement

Table A5. Summary of fuel cell truck main specifications

Group	Fuel cell unit power (kW)	Battery size (kWh)
0	90 kW	12 kWh
1	90 kW	12 kWh
2	90 kW	12 kWh
3	100 kW	20 kWh
4-UD	180 kW	40 kWh
4-RD	180 kW	40 kWh
4-LH	210 kW	70 kWh
5-RD	180 kW	40 kWh
5-LH	210 kW	70 kWh
9-RD	180 kW	40 kWh
9-LH	210 kW	70 kWh
10-RD	180 KW	40 kWh
10-LH	210 kW	70 kWh
11	210 kW	70 kWh
12	210 kW	70 kWh
16	210 kW	70 kWh

TRUCKS' FUEL ECONOMY AND ENERGY EFFICIENCY

Table A6. Diesel fuel consumption for an average 2016 truck using VECTO

l/100 km	Long-haul		Regional delivery		Urban delivery		Municipal utility		Construction	
Group	Low	Ref.	Low	Ref.	Low	Ref.	Low	Ref.	Low	Ref.
0	-	-	20.63	21.17	25.80	27.21	-	-	-	-
1	-	-	20.75	21.93	26.13	29.08	-	-	-	-
2	27.23	31.14	21.09	22.69	26.94	30.78	-	-	-	-
3	-	-	22.02	24.43	31.79	37.59	-	-	-	-
4-UD	29.38	35.05	22.61	24.63	31.74	37.02	75.57	79.72	-	-
4-RD	30.01	35.77	22.89	25.15	32.34	37.86	77.37	80.03	-	-
4-LH	29.23	35.08	22.47	24.58	31.32	36.43	79.50	82.62	-	-
5-RD	22.79	30.04	24.19	29.83	38.15	50.62	-	-	-	-
5-LH	26.17	34.42	27.79	34.60	42.02	56.81	-	-	-	-
9-RD	29.27	36.94	22.98	26.26	-	-	80.97	87.06	-	-
9-LH	29.27	36.94	22.98	26.26	-	-	80.97	87.06	-	-
10-RD	25.90	33.79	27.68	34.07	-	-	-	-	-	-
10-LH	25.90	33.79	27.68	34.07	-	-	-	-	-	-
11	29.40	29.40	23.15	26.42	-	-	81.32	87.42	28.62	33.49
12	26.07	33.99	27.89	34.28	-	-	-	-	33.11	41.99
16	-	-	-	-	-	-	-	-	32.44	41.36

Table A7. Diesel trucks maximum CO_2 reduction potential by 2025 and 2030 relative to 2016.

Group	Maximum CO_2 reduction potential by 2025 relative to 2016 (%)	Maximum CO_2 reduction potential by 2030 relative to 2016 (%)
0	25.22%	27.71%
1	25.60%	28.13%
2	25.55%	28.08%
3	29.24%	32.13%
4 - UD	24.34%	26.74%
4 - RD	35.88%	39.43%
4 - LH	29.51%	32.67%
5 - RD	30.64%	33.92%
5 - LH	29.09%	32.35%
9 - RD	35.89%	39.40%
9 - LH	30.54%	33.75%
10 - RD	31.38%	34.64%
10 - LH	30.10%	33.37%
11	20.68%	22.72%
12	21.03%	23.31%
16	29.73%	32.63%

Table A8. Summary of fuel cell stack cycle-average efficiency for different truck model years and mission profiles.

Model year	Fuel cell stack cycle-average efficiency	
	Long-haul mission profile	Other mission profiles
2022	45%	50%
2030	47%	55%
2040	50%	60%

Table A9. Battery and fuel cell electric trucks weighted energy consumption between 2022 and 2040

Group	Battery-electric trucks (kWh/km)			Fuel cell electric trucks (kg H2/100 km)		
	2022	2030	2040	2022	2030	2040
0	0.58	0.48	0.48	3.33	2.48	2.27
1	0.60	0.50	0.50	3.45	2.57	2.35
2	0.62	0.51	0.51	3.56	2.64	2.42
3	0.80	0.65	0.65	4.59	3.37	3.09
4-UD	0.88	0.66	0.66	5.01	3.45	3.16
4-RD	0.95	0.72	0.72	5.40	3.72	3.41
4-LH	1.06	0.81	0.81	6.73	4.89	4.59
5-RD	1.18	0.87	0.87	6.73	4.51	4.14
5-LH	1.24	0.91	0.91	7.87	5.54	5.21
9-RD	0.96	0.73	0.73	5.46	3.81	3.49
9-LH	1.06	0.80	0.80	6.69	4.89	4.59
10-RD	1.20	0.93	0.93	6.84	4.81	4.41
10-LH	1.26	0.97	0.97	7.98	5.90	5.54
11	1.03	0.81	0.81	5.89	4.20	3.85
12	1.14	0.90	0.90	6.53	4.67	4.28
16	0.95	0.72	0.72	5.41	3.76	3.45

Table A10. Truck battery and hydrogen storage tank size between 2022 and 2040.

Group	Battery size (kWh)			Hydrogen tank size (kg)		
	2022	2030	2040	2022	2030	2040
0	120	100	100	6	4	4
1	180	150	150	9	7	6
2	190	160	160	9	7	6
3	240	200	200	11	9	8
4-UD	260	200	200	12	8	8
4-RD	360	270	270	17	12	11
4-LH (500 km)	680	520	520	34	25	23
4-LH (800 km)	1,110	830	830	54	40	37
4-LH (1,000 km)	1,390	1,040	1,040	68	49	46
5-RD	450	330	330	21	14	13
5-LH (500 km)	800	590	590	40	28	27
5-LH (800 km)	1,300	940	940	63	45	42
5-LH (1,000 km)	1,650	1,190	1,190	79	56	53
9-RD	340	260	260	16	11	10
9-LH (500 km)	670	520	520	34	25	23
9-LH (800 km)	1,090	830	830	54	40	37
9-LH (1,000 km)	1,380	1,040	1,040	67	49	46
10-RD	400	310	310	18	13	12
10-LH (500 km)	810	620	620	40	30	28
10-LH (800 km)	1,310	1,010	1,010	64	48	45
10-LH (1,000 km)	1,670	1,270	1,270	80	59	56
11	380	300	300	17	13	12
12	580	460	460	27	19	18
16	280	210	210	13	9	8

DIESEL AND LNG TECHNOLOGIES' CO_2 COST CURVES

The CO_2 technology cost curves for the diesel and LNG trucks follow a semi-reciprocal function in the form of:

$$f(x) = C + \frac{c}{x - x_0} + b \times x$$

Where x is the CO_2 reduction and the other parameters are summarized in Table A11, Table A12, Table A13, and Table A14.

Table A11. CO_2 cost curves data for diesel trucks in 2025

Group	C	c	X0	b	x_min	x_max	y_min	y_max
4 - RD	-6,858	-2,932	0.42	-20,250	1.70%	35.38%	0	27,664
5 - LH	-7,242	-2,531	0.35	-26,814	1.96%	28.59%	0	27,569
9 - RD	-8,826	-3,908	0.44	-24,668	1.52%	35.39%	0	27,855
10 - LH	-6,821	-2,438	0.35	-22,930	2.07%	29.60%	0	27,809
4 - LH	-3,829	-1,268	0.33	-15,654	2.54%	29.01%	0	27,654
5 - RD	-12,192	-4,874	0.4	-33,786	1.21%	30.14%	0	27,627
9 - LH	-4,507	-1,561	0.34	-16,760	2.26%	30.04%	0	27,858
10 - RD	-11,968	-4,876	0.41	-33,047	1.22%	30.88%	0	27,825
0	-6,858	-2,027	0.3	-20,250	1.70%	24.72%	0	27,664
1	-6,858	-2,060	0.3	-20,250	1.70%	25.10%	0	27,664
2	-6,858	-2,056	0.3	-20,250	1.70%	25.05%	0	27,664
3	-6,858	-2,371	0.35	-20,250	1.70%	28.74%	0	27,664
4 - UD	-6,858	-1,952	0.29	-20,250	1.70%	23.84%	0	27,664
11	-4,507	-1,014	0.23	-16,760	2.26%	20.18%	0	27,858
12	-6,821	-1,653	0.25	-22,930	2.07%	20.53%	0	27,809
16	-8,826	-3,226	0.37	-24,668	1.52%	29.23%	0	27,855

Table A12. CO_2 cost curves data for diesel trucks in 2030

Group	C	c	X0	b	x_min	x_max	y_min	y_max
4 - RD	-6,247	-2,934	0.46	-18,722	1.95%	38.93%	0	26,150
5 - LH	-6,513	-2,533	0.38	-24,321	2.23%	31.85%	0	26,028
9 - RD	-8,070	-3,911	0.48	-22,300	1.74%	38.90%	0	26,339
10 - LH	-6,152	-2,440	0.39	-20,869	2.36%	32.87%	0	26,261
4 - LH	-3,429	-1,268	0.36	-14,323	2.88%	32.17%	0	26,134
5 - RD	-11,103	-4,879	0.44	-30,415	1.40%	33.42%	0	26,102
9 - LH	-4,067	-1,562	0.38	-14,966	2.56%	33.25%	0	26,342
10 - RD	-10,923	-4,881	0.44	-29,868	1.41%	34.14%	0	26,290
0	-6,247	-2,028	0.33	-18,722	0.0195	27.21%	0	26,150
1	-6,247	-2,060	0.33	-18,722	0.0195	27.63%	0	26,150
2	-6,247	-2,057	0.33	-18,722	0.0195	27.58%	0	26,150
3	-6,247	-2,372	0.38	-18,722	0.0195	31.63%	0	26,150
4 - UD	-6,247	-1,952	0.31	-18,722	0.0195	26.24%	0	26,150
11	-4,067	-1,008	0.25	-14,966	0.0256	22.22%	0	26,342
12	-6,152	-1,655	0.27	-20,869	0.0236	22.81%	0	26,261
16	-8,070	-3,227	0.40	-22,300	0.0174	32.13%	0	26,339

Table A13. CO_2 cost curves data for LNG trucks in 2025

Group	C	c	X0	b	x_min	x_max	y_min	y_max
4 - RD	7,744	-4,024	0.47	-28,775	8.06%	38.69%	15,678	43,301
5 - LH	9,723	-2,180	0.38	-17,513	8.30%	32.27%	15,650	43,205
9 - RD	7,103	-4,233	0.48	-25,638	7.89%	38.70%	15,676	43,491
10 - LH	9,917	-2,104	0.39	-13,866	8.41%	33.23%	15,686	43,445
4 - LH	11,657	-1,670	0.37	-21,766	8.85%	32.67%	15,668	43,291
5 - RD	735	-7,159	0.46	-49,423	7.60%	33.73%	15,708	43,263
9 - LH	10,946	-1,986	0.39	-21,880	8.58%	33.65%	15,680	43,494
10 - RD	989	-7,163	0.47	-48,449	7.61%	34.43%	15,702	43,461
0	7,744	-2,549	0.33	-28,775	8.06%	27.04%	15,678	43,301
1	7,744	-2,603	0.33	-28,775	8.06%	27.46%	15,678	43,301
2	7,744	-2,597	0.33	-28,775	8.06%	27.41%	15,678	43,301
3	7,744	-3,113	0.38	-28,775	8.06%	31.44%	15,678	43,301
4 - UD	9,723	-1,635	0.30	-17,513	8.30%	26.08%	15,678	43,233
11	10,946	-1,127	0.26	-21,880	8.58%	22.62%	15,680	43,494
12	9,917	-1,253	0.26	-13,866	8.41%	23.06%	15,686	43,445
16	7,103	-3,347	0.39	-25,638	7.89%	31.97%	15,676	43,491

Table A14. CO_2 cost curves data for LNG trucks in 2030

Group	C	c	X0	b	x_min	x_max	y_min	y_max
4 - RD	30,066	-2,364	0.57	-14,751	21.46%	51.04%	33,479	59,718
5 - LH	30,693	-1,935	0.51	-18,234	21.68%	45.38%	33,436	59,597
9 - RD	29,502	-3,488	0.59	-24,582	21.30%	51.02%	33,484	59,907
10 - LH	30,337	-1,964	0.52	-15,918	21.79%	46.19%	33,475	59,828
4 - LH	32,002	-1,414	0.50	-16,633	22.21%	45.64%	33,463	59,701
5 - RD	28,611	-4,036	0.55	-32,624	21.02%	46.63%	33,509	59,670
9 - LH	31,455	-1,651	0.51	-16,575	21.95%	46.50%	33,487	59,910
10 - RD	28,691	-4,044	0.56	-32,208	21.03%	47.21%	33,505	59,858
0	30,066	-1,156	0.39	-14,751	21.46%	35.72%	33,479	59,718
1	30,066	-1,200	0.40	-14,751	21.46%	36.27%	33,479	59,718
2	30,066	-1,194	0.40	-14,751	21.46%	36.20%	33,479	59,718
3	30,066	-1,615	0.46	-14,751	21.46%	41.50%	33,479	59,718
4 - UD	30,693	-1,065	0.37	-18,234	21.68%	34.46%	33,479	59,640
11	31,455	-544	0.32	-16,575	21.95%	29.91%	33,487	59,910
12	30,337	-843	0.35	-15,918	21.79%	32.11%	33,475	59,828
16	29,502	-2,486	0.48	-24,582	21.30%	42.17%	33,484	59,907

DIRECT MANUFACTURING COSTS

Table A15. Diesel truck direct manufacturing costs calculation

Group	Base model	2018 retail price (€)	Source	2022 adjusted retail price (€) [g]	Direct manufacturing cost (€) [i]
0	DAF LF 170	-	Via Mobilis (2022)	49,900	36,700
1	DAF LF 170	-	Via Mobilis (2022)	49,900	36,700
2	MAN TGL 12.220 (162 kW)	65,000	Lastauto Omnibus (2018)	72,600	53,400
3	-	70,000	ICCT estimate [a]	78,200	57,500
4-UD	-	70,000	ICCT estimate [a]	78,200	57,500
4-RD	Mercedes Antos 1833 L (240 kW)	75,000	Lastauto Omnibus (2018)	83,800	61,600
4-LH	MAN TGX 18.4260 (338 kW)	98,900	Lastauto Omnibus (2018)	110,400	81,200
5-RD	-	80,000	ICCT estimate [b]	89,300	65,700
5-LH	Mercedes Actros 1848 LS (350 kW)	103,000	Lastauto Omnibus (2018)	115,000 [h]	84,600
9-RD	-	81,000	ICCT estimate [c]	90,400	66,500
9-LH	Mercedes Actros 2545 L (330 kW)	105,000	Lastauto Omnibus (2018)	117,200	86,200
10-RD	-	86,000	ICCT estimate [d]	96,000	70,600
10-LH	-	109,000	ICCT estimate [e]	121,700	89,500
11	-	135,000	ICCT estimate [f]	150,700	110,800
12	Volvo FH 16-750 XL (550 kW)	140,000	Lastauto Omnibus (2018)	156,300	114,900
16	Mercedes Arocs 3245 (330 kW)	155,000	Lastauto Omnibus (2018)	173,000	127,200

[a] Assumed to be between the retail price of group 2 and 4-RD.
[b] 23,000 € cheaper than the retail price of group 5-LH, similar to the difference in retail price between groups 4-LH and 4-RD.
[c] 6,000 € more expensive than the retail price of group 4-RD, similar to the difference in retail price between groups 9-LH and 4-LH.
[d] 6,000 € more expensive than the retail price of group 5-RD, similar to the difference in retail price between groups 9-RD and 4-RD.
[e] 6,000 € more expensive than the retail price of group 5-LH, similar to the difference in retail price between groups 9-LH and 4-LH.
[f] 5,000 € cheaper than the retail price of group 12, similar to the difference in retail price between groups a rigid and tractor truck.
[g] Retail prices in 2022 are adjusted assuming an 11.6% increase relative to 2018. This is derived from the difference in retail prices between a 2022 model year 5-LH tractor-truck and its 2018 equivalent.
[h] Lastauto Omnibus (2022)
[i] The direct manufacturing costs are calculated assuming an indirect cost multiplier of 1.36 based on Ricardo Strategic Consulting (2022).

Table A16. Calculating the chassis direct manufacturing costs of zero-emission trucks

Group	Powertrain (€)	HVAC, elec, air brakes (€)	Driveline, cab, chassis (€)	Assembly (€)	ICM (€)	Zero-emission chassis (€)
	43%	6%	18%	7%	26%	
0	21,457	2,994	8,982	3,493	12,974	12,475
1	21,457	2,994	8,982	3,493	12,974	12,475
2	31,206	4,354	13,063	5,080	18,869	18,143
3	33,607	4,689	14,068	5,471	20,320	19,539
4-UD	33,607	4,689	14,068	5,471	20,320	19,539
4-RD	36,007	5,024	15,073	5,862	21,772	20,934
4-LH	47,482	6,625	19,876	7,730	28,710	27,606
5-RD	38,408	5,359	16,078	6,252	23,223	22,330
5-LH	49,450	6,900	20,700	8,050	29,900	28,750
9-RD	38,888	5,426	16,279	6,331	23,514	22,609
9-LH	50,410	7,034	21,102	8,206	30,481	29,308
10-RD	41,288	5,761	17,283	6,721	24,965	24,005
10-LH	52,331	7,302	21,906	8,519	31,642	30,425
11	64,813	9,044	27,131	10,551	39,189	37,682
12	67,214	9,379	28,136	10,942	40,641	39,078
16	74,415	10,383	31,150	12,114	44,995	43,265

Notes: The retail price partition is derived based on Ricardo Strategic Consulting (2022). The zero-emission chassis direct manufacturing cost is calculated as the sum of the *Driveline, Cab, Chassis costs* and the *Assembly* cost.

Table A17. Direct manufacturing costs of the main powertrain components for zero-emission trucks in 2022, 2030, and 2040 (Sharpe & Basma, 2022). Numbers are adjusted for inflation assuming 10% inflation in the EU between 2020 and 2022.

Component	2022	2030	2040
Energy battery	160 €/kWh	90 €/kWh	55 €/kWh
Power battery	407 €/kWh	250 €/kWh	223 €/kWh
Fuel cell stack	460 €/kW	230 €/kW	100 €/kW
Hydrogen storage tanks	900 €/kg	525 €/kg	450 €/kg
Electric drive	58 €/kW	17 €/kW	14 €/kW
Power electronics	25 €/kW	25 €/kW	25 €/kW

OPTIMAL TECHNOLOGY MARKET SHARE

Table A18. Summary of the MPW and CO_2 emissions per VECTO group

Group	Mileage (km)	Payload (kg)	MPW	CO_2 (g/t.km)
0	40,000	686.32	0.017	778.06
1	62,000	1,374.2	0.053	433.46
2	62,000	1,860.32	0.072	358.35
3	62,000	2,757.5	0.106	241.96
4-UD	60,000	2,650	0.099	306.58
4-RD	78,000	3,180	0.154	198.28
4-LH	98,000	7,420	0.453	106.65
5-RD	78,000	10,258	0.498	84.36
5-LH	116,000	13,842	1.000	56.79
9-RD	73,000	6,280	0.286	111.20
9-LH	108,000	13,400	0.901	65.33
10-RD	68,000	10,258	0.434	89.28
10-LH	107,000	13,842	0.922	59.43
11	75,000	3,600	0.168	674.81
12	105,000	10,258	0.671	108.53
16	60,000	9,810	0.367	110.87

Figure A1. Optimal technology market share per VECTO group under the adopted policies scenario.

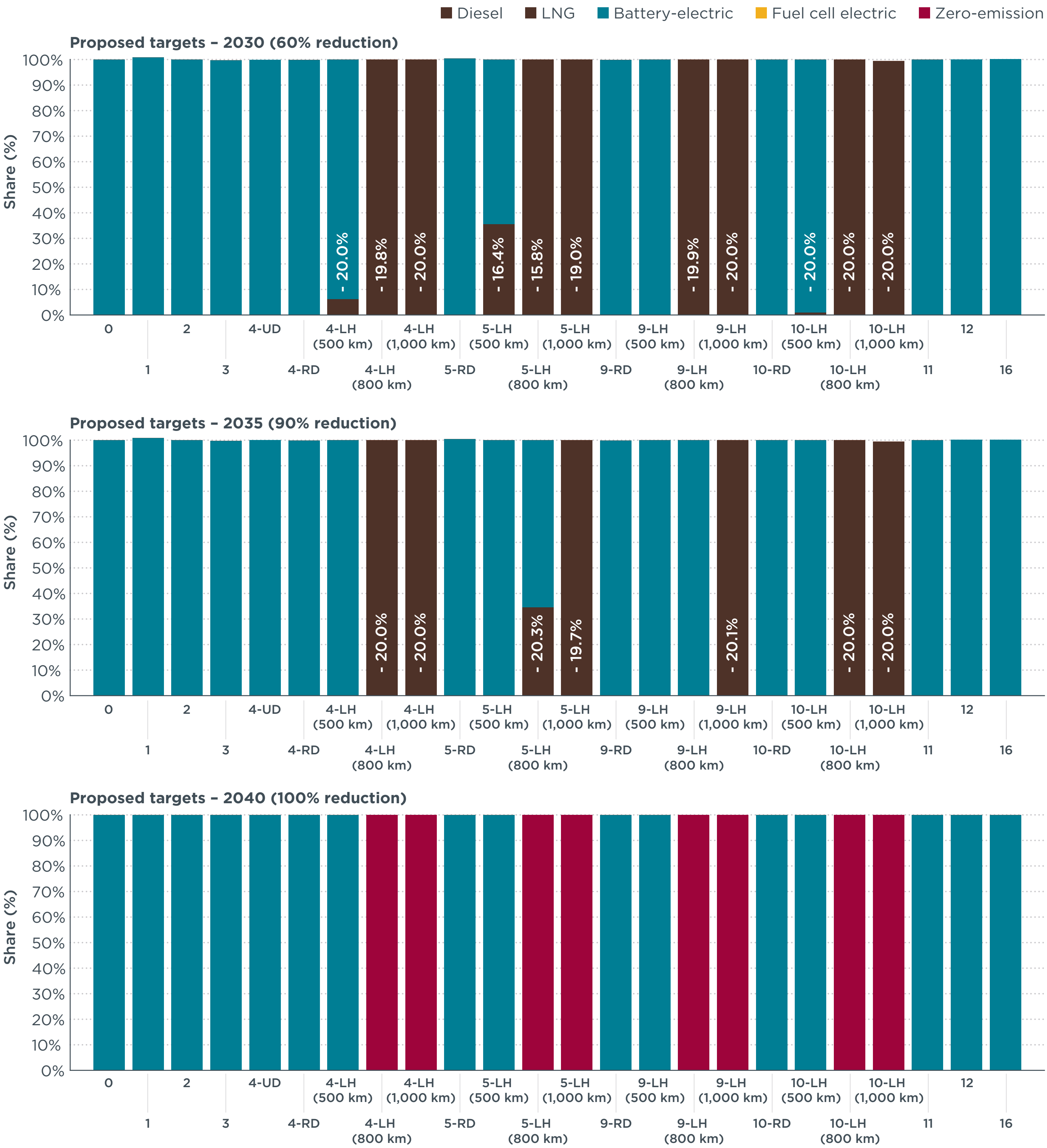

Figure A2. Optimal technology market share per VECTO group under the proposed targets scenario.

CONSUMER COST-BENEFIT ANALYSIS

Table A19. Summary of truck residual value assumptions

Component	Lifetime	Residual value after first use	Residual value after second use
Base glider and Powertrain [a)]	15 years	46%	0%
Battery [b)]	4,000 cycles	43%	15%
Fuel cell [c)]	30,000 hours	56%	0%
Hydrogen tank [d)]	5,000 cycles	74%	22%

[a)] Analytical approach based on Basma, Zhou, et al. (2022)
[b)] The battery cycle life is an ICCT assumption. The residual value after first use is estimated based on electric bus battery aging from (Basma, Haddad, et al., 2022) and the residual value after second use based on Burke & Zhao (2017).
[c)] Lifetime based on future technology improvement Burke (2020). Residual value after first use is calculated assuming trucks operate for 10 hours per day for 5 days a week.
[d)] Lifetime based on Pohl and Ridell (2019) and residual value is calculated assuming one cycle per day and 5 days of operation per week.

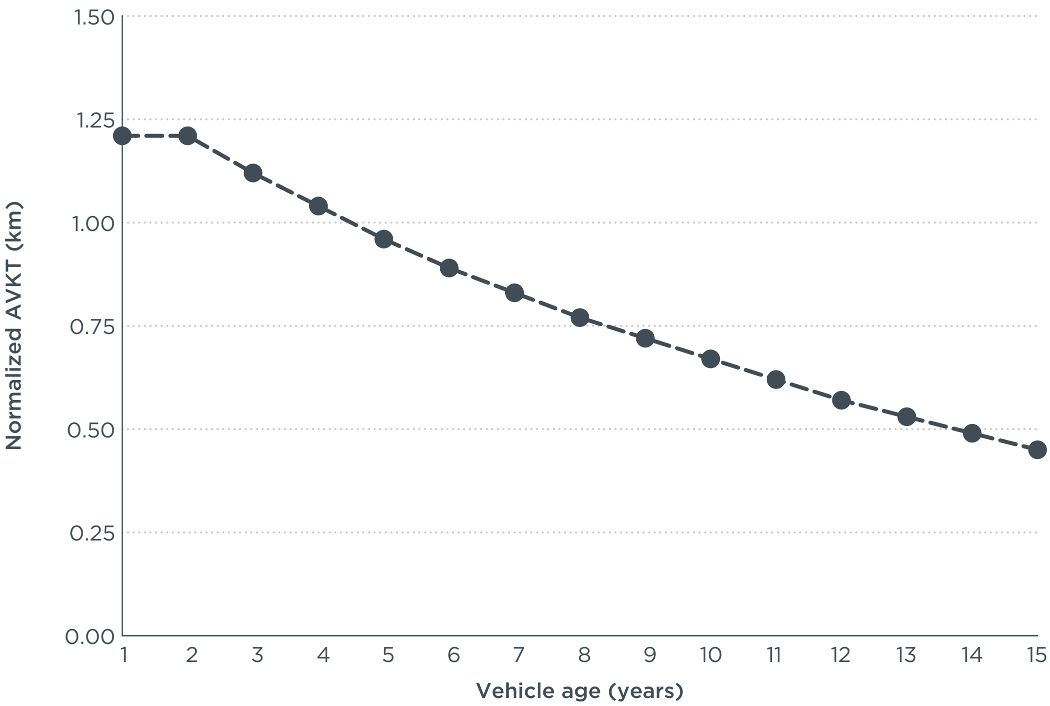

Figure A3. Vehicle normalized annual kilometers traveled (AVKT) cost relative to the reference annual mileage.

Table A20. Summary of the first five-year average maintenance costs per VECTO group and powertrain technology assumed constant between 2030 and 2040

Group	Diesel (€/100 km)	LNG (€/100 km) [f]	Batter-electric (€/100 km)	Fuel cell electric (€/100 km)
0 [a]	11.00	12.10	7.50	7.89
1 [b]	11.00	12.10	7.50	7.89
2 [b]	11.00	12.10	7.50	7.89
3 [c]	15.77	17.35	10.51	11.05
4-UD [c]	15.77	17.35	10.51	11.05
4-RD [c]	15.77	17.35	10.51	11.05
4-LH [c]	15.77	17.35	10.51	11.05
5-RD [d]	18.50	19.43	13.24	13.78
5-LH [d]	18.50	19.43	13.24	13.78
9-RD [c]	15.77	17.35	10.51	11.05
9-LH [c]	15.77	17.35	10.51	11.05
10-RD [d]	18.50	19.43	13.24	13.78
10-LH [d]	18.50	19.43	13.24	13.78
11 [c]	15.77	17.35	10.51	11.05
12 [d]	18.50	19.43	13.24	13.78
16 [e]	11.14	11.93	7.73	7.73

[a] Diesel and BET maintenance costs of VECTO group 0 are adopted from (Basma, Rodríguez, et al., 2022). FCET maintenance costs are assumed to have the same cost reduction as a rigid truck relative to its diesel equivalent.
[b] Diesel and BET maintenance costs of VECTO groups 1 and 2 are assumed like those of VECTO group 1
[c] Diesel and BET maintenance costs for rigid trucks with GVW above 12 tonnes are adapted from (Basma, Saboori, et al., 2021) excluding the trailers' tires maintenance costs. Similarly, FCET maintenance costs are adopted from Basma, Zhou, et al. (2022).
[d] Diesel and BET maintenance costs for tractor-trailers are adapted from Basma, Saboori, et al. (2021). Similarly, FCET maintenance costs are adopted from (Basma, Zhou, et al., 2022).
[e] Diesel and BET maintenance costs for VECTO group '16' are adapted from Burnham (2020) for a dump truck. FCETs are assumed to have the same maintenance costs as BETs.
[f] LNG trucks' maintenance costs are assumed 5% higher than diesel trucks' maintenance costs for tractor-trailers and 10% higher for all other VECTO groups. These figures are adapted from Burnham (2020).

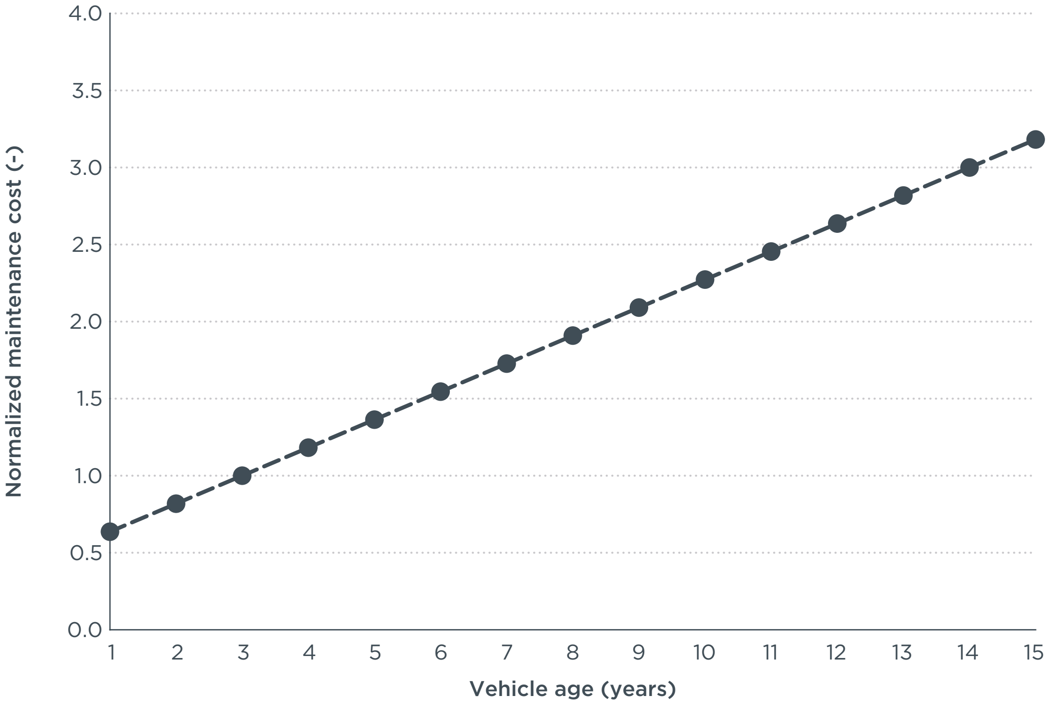

Figure A4. Vehicle normalized maintenance cost relative to the average first-user maintenance cost.