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An economic and environmental analysis of retrofitted fuel cell electric heavy-duty trucks

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HIGHLIGHTS

- Subsidized retrofitting is economically viable when hydrogen prices are below 5 $\frac{€}{kg_{H2}}$.
- Subsidies are crucial for the economic and carbon abatement potential of retrofitting.
- Early retrofittings are better for cost-effective carbon reduction.
- Late retrofittings are best from a cost perspective.

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ABSTRACT

The decarbonization of the freight transportation sector is posing significant challenges. Technical, economic, and environmental assessments have been conducted to determine the impact that alternative powertrains are having on the heavy-duty vehicle sector. However, the literature lacks information on how retrofitting might affect the outcomes. This article analyzes the effect of retrofitting on economic and environmental dimensions, both individually and in combination. We determine the most advantageous time frame for economically and environmentally effective retrofitting while considering potential trade-offs. Our methodology incorporates Total Cost of Ownership, Life Cycle Assessment, and Total Cost of Carbon Abatement. In addition to retrofitting costs, we also account for purchase costs, fuel costs, hydrogen prices, residual values, and other relevant cost categories in our model. Our findings indicate that the optimal timing of retrofitting in terms of both economic and environmental factors largely depends on the method of hydrogen production that is utilized. For fuel cell electric trucks to remain competitive, it is necessary to maintain a hydrogen price below 5 $\frac{€}{kgH_2}$ when subsidies are in place. Our results show that, when no subsidies are in place, retrofitted fuel cell electric trucks are not competitive at all. Policymakers should offer greater certainty to fleet operators, should promote increased investments in renewable hydrogen production to reduce the levelized cost of hydrogen, and should approach policy instruments more comprehensively.

1. Introduction

The challenge of reducing Greenhouse Gas (GHG) emissions in the transportation sector applies to the road transportation sector on a global scale. In the European Union only few countries have managed to slightly decrease emissions since 1990, such as Sweden, Switzerland, Germany, the Netherlands, and Finland [1]. All other European countries have increased their emissions. The same pertains to the biggest markets like China [2] and the United States [3].

Despite all efforts in Germany to reduce GHG emissions, the transportation sector has been the least successful in total emission reductions since 1990 [4]. While on average GHG emissions in Germany were reduced by 38.7 % between 1990 and 2022, the country's transportation sector showed a decrease of only 9.4 %, the lowest reduction compared to the other sectors (energy sector: 46.1 %, industry: 41.1 %, buildings: 46.8 %). As a consequence, the transportation sector increased its share of the overall GHG emissions from 13 % in 1990 to 20 % in 2022 [5].

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Nomenclature

Symbols

$CAPEX_{H2}$ CAPEX for a water electrolysis plant
$CAPEX_{ICET}$ CAPEX of an internal combustion engine truck
CO_2 Carbon Dioxide
CRF Capital Recovery Factor
$C_{Fuel,t,k,l}$ Fuel costs for a heavy-duty vehicle in time period t, gross vehicle weight rating k and drivetrain technology l
$C_{Insurance,t,k,l}$ Costs for insurance in time period t, gross vehicle weight rating k and drivetrain technology l
$C_{OM,t,k,l}$ Costs for maintenance and repair per kilometer driven in time period t, gross vehicle weight rating k and drivetrain technology l
$C_{Tax,t,k,l}$ Taxes for a heavy-duty vehicle in time period t, gross vehicle weight rating k and drivetrain technology l
$C_{Toll,t,k,l}$ Costs per kilometer toll road in time period t, gross vehicle weight rating k and drivetrain technology l
$C_{Retrofitting,t,k,l}$ Retrofitting costs for a vehicle of weight class k and drivetrain technology l in time period t
$C_{Toll,k,Diesel}$ Costs per kilometer toll road for diesel trucks
$C_{Toll,k,FC}$ Costs per kilometer toll road for fuel cell trucks
I_{markup} Integration markup
$LCOH$ Levelized Costs of Hydrogen
$OPEX_{H2,t}$ OPEX of hydrogen production in time period t
$OPEX_{t,k,l}$ OPEX of a heavy-duty vehicle in time period t, gross vehicle weight rating k and drivetrain technology l
PM_{10} Particulate Matter < 10 μm (Coarse Particular Matter)
$PM_{2.5}$ Particulate Matter < 2.5 μm (Fine Particles)
$P_{Component}$ Component size e.g. (power or capacity etc.)
RV_T Residual value of vehicle with total vehicle lifetime T
$RV_{k,l}$ Residual value of vehicle in weight class k equipped with drivetrain technology l
SO_x Sulfur Oxides
$Subsidy$ Subsidy amount received for vehicle retrofitting with regard to upper limit
TCO_{Truck} Total cost of Ownership of a truck
T Total vehicle lifetime in years
VKT_t Vehicle Kilometers Traveled in time period t
VKT Vehicle Kilometers Traveled
V_{Diesel} Fuel consumption on 100 km yielded in liter (diesel)
V_{H2} Fuel consumption on 100 km yielded in kg (hydrogen)
V_l Fuel consumption on 100 km yielded in liter for drivetrain technology l
α_k Share of VKT driven on toll roads per weight class k
$\eta_{TtW,Diesel}$ Tank-to-Wheel efficiency of a diesel drivetrain
$\eta_{TtW,FC}$ Tank-to-Wheel efficiency of a fuel cell electric drivetrain
ε_{diesel} Indicator of technology maturity and infrastructure density of diesel electric truck
$\varepsilon_{k,FC}$ Indicator of technology maturity and infrastructure density of fuel cell electric trucks with gross vehicle weight rating k
ε_l Indicator of technology maturity and infrastructure density of drivetrain technology l
$a_{k,l}$ Empirical coefficient for the RV determination of a vehicle in weight class k equipped with drivetrain technology l
$b_{k,l}$ Empirical coefficient for the RV determination of a vehicle in weight class k equipped with drivetrain technology l
$c_{Component}$ Specific component costs
c_l Specific fuel costs
e_{Diesel} Volumetric energy content of diesel
e_{H2} Gravimetric energy content of hydrogen
i Discount rate
k Gross vehicle weight rating
l Drivetrain technology
$m_{h2,t}$ Mass of hydrogen produced during time period t
t Time period
ton Metric tonne

Abbreviations

AEL Alkaline Electrolysis
BET Battery Electric Truck
BEV Battery Electric Vehicle
BoM Bill of Materials
CAPEX Capital Expenditures
CAT Catenary Vehicle
CCS Carbon Capture and Storage
CG Coal Gasification
FCET Fuel Cell Electric Truck
FCEV Fuel Cell Electric Vehicle
GEDEL Grid Electricity Decentralized Electrolysis
GHG Greenhouse Gas
GVWR Gross Vehicle Weight Rating
GWP Global Warming Potential
H2M H2Mobility
HDV Heavy-Duty Vehicle
HET Hybrid Electric Truck
HV High Voltage
ICET Internal Combustion Engine Truck
LCA Life Cycle Assessment
LCECEL Low-Carbon Electricity Centralized Electrolysis
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
LCOE Levelized Cost of Energy
LCOH Levelized Cost of Hydrogen
LNG Liquid Natural Gas
LV Low Voltage
NPV Net Present Value
OBC On-Board Charger
OEM Original Equipment Manufacturer
OPEX Operating Expenditures
PDU Power Distribution Unit
PEM Polymer Electrolyte Membrane
PEMEL Polymer Electrolyte Membrane Electrolysis
RES Renewable Energy Sources
RV Residual Value
SMR Steam Methane Reforming
TCA Total Cost of Carbon Abatement
TCO Total Cost of Ownership
TTW Tank-To-Wheel
WACC Weighted Average Cost of Capital
WTT Well-To-Tank
WTW Well-To-Wheel
ZEV Zero-Emission Vehicle

Heavy-Duty Vehicles (HDVs) (class N3: permissible total weight greater than 12 tons) account for just 1 % of the registered vehicles in Germany but are responsible for approximately 25 % of the country's annual GHG emissions in transportation. Hence, this vehicle class is a strong lever for reaching the emission goals, and meaningful measures should attempt to target it. Based on an expected increase in road freight traffic of over 300 % between 2010 and 2050, the distances traveled will not decrease [6]. Instead, the emissions per driven kilometer will have to be targeted. Therefore, the transition of HDVs towards zero-emission drivetrains appears to be a solution. The question of which drivetrain to use for HDVs is not only environmentally justified but also economically motivated [5].

Based on climate policies and the developments in freight loads, there exists a clear need for Zero-Emission Vehicles (ZEVs) among HDVs. For this vehicle class, the use of fuel cells as energy converters is an alternative to battery electric drives. Particularly for long-distance routes, the use of fuel cell electric drives will be inevitable, as these combine the advantages of long ranges and short refueling times of conventional drives with the possibility of emission-free operation as known from Battery Electric Vehicles (BEVs). However, commercial vehicle Original Equipment Manufacturers (OEMs) will not begin mass production of Fuel Cell Electric Trucks (FCETs) until the late 2020s. Hyundai was the first manufacturer to launch its Hyundai XCient Fuel Cell in Germany in 2022 [7]. MAN will not launch its first model before 2025 [8] and Daimler Truck, the largest commercial vehicle manufacturer in Europe, announced its GenH2 for the second half of the current decade [9]. Due to this late market penetration, the share of ZEVs in the Heavy-Duty Vehicle (HDV) fleets on Germany's streets will not be high enough to meet the climate goals. As a consequence, short-term market alternatives for FCETs have to be established.

Retrofitting targets the conversion of existing vehicles with conventional drivetrains into fuel cell electric drivetrains. The first retrofitting prototypes have already been presented [10–12]. However, the techno-economic research still focuses on vehicles initially produced as ZEVs by OEMs [13–15]. In addition to this research gap on retrofitting, the current research focus is not suited to the analysis of retrofitted trucks. Most existing studies evaluate the economic and the environmental impact of different drivetrains and contrast them in order to determine which topology is economically optimal for the fleet operator and whether this is opposed to or in line with the environmentally ideal configuration [13–15].

However, the above-mentioned political and social goals and the coincidental transportation developments leave no doubt that ZEVs need to become more prevalent among HDVs. The key question that remains unanswered is: When should vehicles be retrofitted to work with zero emissions? The contribution of this article is to investigate whether it is preferable to retrofit a new truck, which automatically implies a new base for the vehicle, or whether trucks that were previously in use should be retrofitted in order to extend the vehicle's lifetime. Thus, both retrofitting timings need to be analyzed from an economic, environmental, and a combined perspective, which leads to the following research questions:

1. What is the optimal age of heavy-duty trucks for retrofitting with fuel cell electric drives from both an economic and an environmental perspective?
2. How could potential trade-offs with regard to economic and environmental performance affect the decision-making process on retrofitting?

In order to analyze the retrofitting of HDVs with a fuel cell electric drivetrain economically and environmentally in a comprehensive manner, we first develop a Total Cost of Ownership (TCO) model, which considers important parameters, such as purchase costs, resale value, and operating costs. Second, based on the assumptions made for the TCO model, a Life Cycle Assessment (LCA) with a Well-To-Wheel (WTW) approach for the considered pathways is conducted, so that environmental effects are covered and GHG emissions can be determined. Third, the results of the aforementioned methodologies are combined to calculate the Total Cost of Carbon Abatement (TCA). The developed model is limited to the German market, as numerous input parameters vary greatly when different transportation markets are considered. Furthermore, different scenarios will be developed and their impact on the economic and environmental attractiveness of different conversion dates in an HDV's lifetime will be investigated.

2. Background and literature review

2.1. Retrofitting of heavy-duty vehicles with a fuel cell electric powertrain

Retrofitting of HDVs is not an innovative concept developed due to the necessity for zero-emission commercial vehicles: For decades now, trucks have been retrofitted in order to suit alternative applications. Municipal utility vehicles, such as those used by firefighters or garbage collectors, are only one example of the long history of retrofitted vehicles [16]. However, the retrofitting process discussed in this article is not yet commercially widespread. In contrast to the modification of the vehicle itself in order to serve a different purpose, the Fuel Cell Electric Truck (FCET) has the same purpose as an Internal Combustion Engine Truck (ICET); only the drivetrain is new. As explained earlier, it will take more time for the market ramp-up for FCETs from OEMs. In order to bridge the development periods of the OEMs, several smaller companies from the automotive industry or even new market participants have begun offering FCETs that are retrofitted from conventional diesel combustion engines [17].

To our knowledge, the retrofitting process has not yet been described in the scientific literature. Hence, information on the current process can only be gathered from manufacturers' websites [18–22] or through expert interviews, which describe it superficially and are largely indistinguishable across sources. A retrofitting process that can be found on websites of various companies, and which is also the basis for this article, is depicted in Fig. 1. Other companies offering truck retrofitting, such as Enginius [23], Hyzon [19], or Pepper Motion [20], publish less information on their websites, but the processes are similar to that of Quantron [18].

2.2. Total cost of ownership of heavy-duty vehicles

The TCO analysis is a method that is widely used to evaluate long-term investments. It was mainly elaborated by Ellram and Perrott Siferd [24] as a tool to determine the entire costs that arise from the purchase of a product. The TCO concept not only takes into account the purchase costs but also considers costs induced by the acquisition. It has been widely used in the literature as a method to comprehensively evaluate the costs that consumers face when deciding to purchase passenger cars [25–28]. Recently, several studies have been published related to HDVs and using the TCO method to evaluate the feasibility of purchasing an HDV for long-haul carriers.

Noll et al. [29] analyze the economic competitiveness between commercial vehicles with alternative drivetrains and conventional diesel fueled vehicles. They consider FCETs, Battery Electric Trucks (BETs), Hybrid Electric Trucks (HETs), and Internal Combustion Engine Trucks (ICETs) fueled by natural gas. The TCO is determined based on the Capital Expenditures (CAPEX), the Operating Expenditures (OPEX), the residual value, and the distances driven per year. The annualized costs are calculated by multiplying the CAPEX and the Residual Value (RV) by the annuity factor, whereas the sum of the discounted OPEX is averaged over the truck's lifetime. The study analyzes the TCO in different European countries. For Germany, the FCET is significantly more expensive than the ICET.

Gunawan and Monaghan [13] extend this economic analysis and compare various conventional and alternative drivetrains from a technical, an economic, and an environmental perspective. This study focuses on truck fleets, rather than individual vehicles, in the quarrying sector. The economic consideration is based on a TCO analysis, and for an environmental assessment the WTW GHG emissions are analyzed. The TCO includes fuel costs, vehicle costs, infrastructure costs, and maintenance costs, as well as the residual value of the vehicle. Another focus of their study is electricity and fuel production and how different combinations, e.g., on-site electricity production and grid electricity, affect the TCO and GHG emissions. As the study again analyzes newly produced vehicles only, it aims to establish whether FCETs are economically competitive with ICETs in general. The authors find that FCETs are not

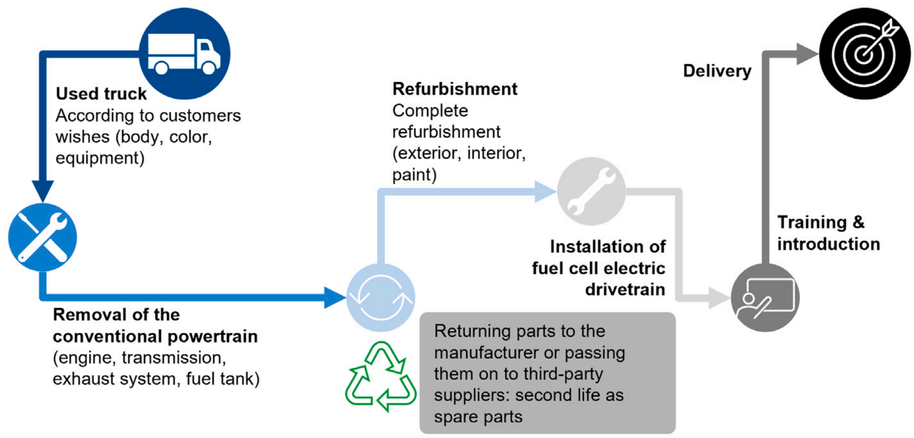

Fig. 1. Retrofitting process for the conversion of a conventional commercial vehicle to a fuel cell electric heavy duty vehicle [18].

competitive. Besides that, Gunawan and Monaghan [13] combine the economic and the environmental analysis into one indicator: the TCA. This figure relates the emission reduction of alternative drivetrain technologies to their cost increase and thereby yields an option to price the CO_2 emissions saved.

In their study, Basma et al. [30] compare the TCO for tractor trailers in Europe depending on the underlying drivetrain technology. The subject of the analysis are BETs and ICETs. Again, this study compares new vehicles and its goal is to identify scenarios for which the Battery Electric Truck (BET) is economically dominant over the conventionally driven truck. The TCO analysis is based on a Net Present Value (NPV) approach. Only the time period of the first-buyer's use (five years) is considered and the focus lies on costs, which differ between the two drivetrain topologies. Therefore, it is a comparison rather than the determination of the real TCO. The analysis is structured into fixed and variable costs. The fixed costs consider the vehicle purchase, truck financing, residual value, registration and ownership taxes, and fixed tolls. Operational costs include the distance-based road tolls, maintenance costs, fuel and electricity costs, and infrastructure costs for charging. The authors find that in the baseline scenario BETs and ICETs will reach TCO parity in Germany by the end of this decade. Finally, different political measures are analyzed within various scenarios to determine their impact on the TCO parity.

Alonso-Villar et al. [14] have investigated whether it is technically, economically, and environmentally feasible to use alternative HDVs in Iceland. Besides calculating the TCO of 10 different powertrains, they have also applied a WTW analysis, while examining how the resource availability of Iceland will be affected and maintaining sufficient capacities of fuel and electricity supply along the way. The authors underline that regional truck activity for ranges of 500 km is most likely to be met by FCETs, while BETs should be utilized for short-haul purposes. However, the authors state that both drivetrains affect the power grid capacity to such an extent that it could become prone to overloading. Furthermore, it is shown that regionally deployed BETs and FCETs cause the least amount of emissions, except for SO_x and PM_{10}. In contrast, especially Fuel Cell Electric Vehicles (FCEVs) for regional purposes show the highest TCO of all considered drivetrains or fuel types with approx. 2.8 million USD in comparison to ICETs with approx. 1.5 million USD, which can be explained by the high hydrogen costs assumed by the authors.

Finding the optimal dimensions of a fuel cell drivetrain and optimizing it with reference to the TCO has been considered by Anselma and Belingardi [15]. Based on present and future values of fuel cells, batteries, and hydrogen storage systems, as well as hydrogen and electricity costs, the optimal drivetrain has been identified. Results suggest that BETs currently surpass FCETs in terms of cost minimization, since component and fuel costs are remarkably higher than those of their BET counterparts. For future scenarios in 2030 and 2050 however, the authors state that FCETs will be cost competitive in all considered cases. The only exception is when hydrogen prices increase and electricity prices fall.

Gnann et al. [31] applied a TCO model, determined WTW CO_2 emissions, and considered technological readiness for diesel, Liquid Natural Gas (LNG), fuel cell, battery electric, and Catenary Vehicles (CATs). The study includes only vehicles with a Gross Vehicle Weight Rating (GVWR) of 40 tons. It also considers infrastructure costs, as they are of particular relevance for CATs. According to their results, battery-electric and CATs show the lowest costs of all considered drivetrains, while fuel cell and LNG vehicles have higher costs. For decreasing costs of FCETs, Gnann et al. [31] point out that, on the one hand, hydrogen prices have to decrease or, on the other hand, Tank-To-Wheel (TTW) efficiency of the drivetrain has to be improved. Despite showing the lowest TCO caused by battery-electric and CATs for longer routes, Gnann et al. [31] emphasize in general the challenges associated with building up the infrastructure for ZEVs such as FCETs, BETs and CATs.

A growing number of mostly recent studies have applied economic assessments of HDVs with different powertrains, utilizing TCO as an integral part of their analyses [32–47]. A few of these studies either employed an LCA in conjunction with a TCO [32,33,39,40,43,46,47], applied an LCA exclusively [48], investigated environmental effects without an LCA [37,44,45], or conducted a combined assessment by determining the TCA [32,39,44]. In addition to FCETs, certain studies drew comparisons between fuel cell powertrains and hydrogen combustion engines [36–38,46]. The impact of policies, technological advancements, and potential market scenarios was addressed [34,36,37,40–42, 44–47,49], as was the granular technical design of vehicles, driving cycles and performance [32,35,36,39,40,46]. Table 1 presents the analyzed articles from the literature based on economic and environmental assessments of HDVs.

2.3. Life cycle assessment of heavy-duty vehicles

As part of the system boundaries of an LCA, in the literature we can find two research streams, which can be classified into an LCA of the vehicle cycle and fuel cycle. Although several studies have covered the vehicle cycle [50–55], we only set the focus on the fuel cycle, since currently there is a lack of data to holistically determine the vehicle cycle's environmental impact with validity. Additionally, evidence suggests that the vehicle cycle has minimal contribution to overall emissions throughout the vehicle's lifetime [56]. Hence, we only refer to studies which have approached the research stream of the fuel cycle.

Table 1
Literature review on economic and environmental assessments of heavy-duty vehicles.

References	Method	Vehicle type			Powertrain type						Country	Feasibility analysis		
		LDV	MDV	HDV	ICEV	BEV	FCEV	(P)HEV	NG	Other		Technical	Economic	Environmental
Alonso-Villar et al. [14]	TCO, LCA	x	x	x	x	x	x	x	x	Biodiesel, Renewable Diesel 20, Renewable Diesel 100, CNG, LNG	Iceland	x	x	x
Anselma and Belingardi [15]	TCO	–	–	x	–	x	x	–	–	–	–	x	x	–
Ayca and Dincer [48]	LCA	x	–	x	–	–	x	–	–	–	–	–	–	x
Bai et al. [32]	TCO, LCA, TCA	–	–	x	x	x	x	–	–	–	China	x	x	x
Bai et al. [33]	TCO, LCA	–	–	x	x	x	x	–	–	Methanole and ammo-nia for ICEV and BEV	China	–	x	x
Basma et al. [30]	TCO	–	–	x	x	x	–	–	–	–	6 European countries + UK	–	x	–
Burke et al. [34]	TCO	–	x	x	x	x	x	–	–	–	United States	–	x	–
Ferrara et al. [35]	TCO	–	–	x	–	–	x	–	–	–	–	x	x	–
Gnann et al. [31]	TCO	–	–	x	x	–	x	–	x	Catenary hybrid vehicles	Germany	–	x	x
Gunawan and Monaghan [13]	TCO, LCA, TCA	–	–	x[1]	x	x	x	x	–	Diesel-hydrogen dual-fuel engine heavy-duty truck	Ireland	x	x	x
Lago Sari et al. [36]	TCO	–	–	x	x	–	x	–	–	Hydrogen combustion engine	US, China, India, Brazil, Germany (vehicle cycles)	x	x	–
Ledna et al. [37]	TCO	–	x	x	x	x	x	x	–	Hydrogen combustion engine	United States	–	x	x
Magnino et al. [38]	TCO	–	–	x	x	x	x	–	–	Hydrogen combustion engine	Finland	–	x	–
Mojtaba Lajevardi et al. [39]	TCO, LCA, TCA	–	–	x	x	x	x	x	x	In total 16 powertrain types	Canada	x	x	x
Mu et al. [49]	TCO	–	–	x	–	x	x	–	–	–	China	–	x	–
Nan et al. [40]	TCO, LCA	–	–	x	–	x[2]	x[2]	–	–	–	China	–	x	x
Noll et al. [29]	TCO	x	x	x	x	x	x	x	x	–	10 European countries	x	x	–
Parviziomran and Bergqvist [41]	TCO	–	–	x	x	x	x	–	–	–	Sweden	–	x	–
Rout et al. [42]	TCO	x	–	x	x	x	x	–	–	–	United Kingdom	–	x	–
Syré and Göhlich [43]	TCO, LCA	–	–	x	x	x	x	–	–	–	Germany	–	x	x
Teng et al. [44]	TCO,TCA	–	–	x	x	–	x	–	–	–	China	–	x	x
Wang et al. [45]	TCO	–	x	x	x	x	x	–	–	–	United Kingdom	–	x	x
Xue et al. [46]	TCO, LCA	–	–	x	x	x	x	–	–	Hydrogen combustion engine	China	–	x	x
Zhang et al. [47]	TCO, LCA	–	–	x	x	x	x	x	–	Battery-electric catenary	China	–	x	x

[1] Quarry Trucks.
[2] Hybridization.

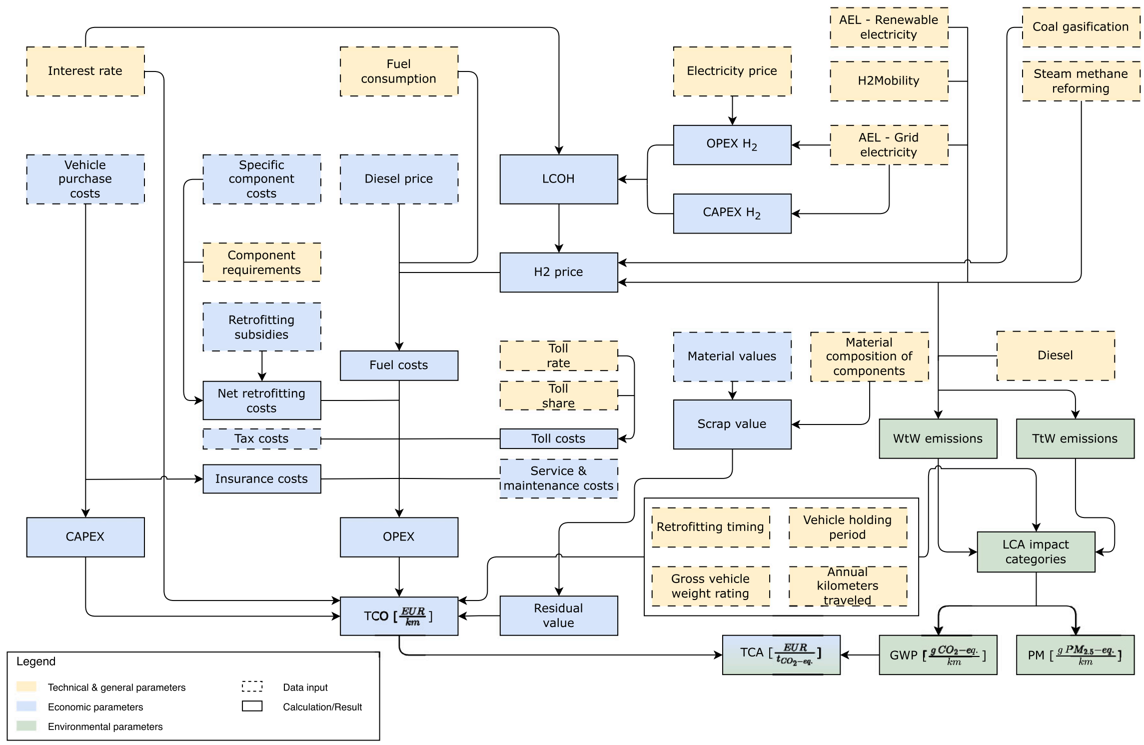

Fig. 2. Model Overview.

The production of hydrogen is the subject of numerous studies. LCA is frequently used as a method to evaluate the environmental impact of the various production paths. The objective of most publications includes the comparison of different production paths and the establishment of a relative ranking with regard to their environmental impact. Thereby the processing stages with the greatest impact are identified and possible improvements are developed [57].

LCA considerations often attempt to cover the entire value chain. For example, Cetinkaya et al. [58] begin with the raw material extraction and the construction of the production facilities, but also consider the operation of such facilities. Analogously, Dufour et al. [59] consider the construction of production plants, including material procurement, raw material mining, and energy production for the operating stages. Kudoh and Ozawa [60] consider the transportation, compression, and refueling of hydrogen.

In terms of the production pathways considered, nearly all studies compare conventional processes, which are the industry standard today, to alternative methods, which are expected to have a lower economic impact. Steam Methane Reforming (SMR) [58,59,61,62] and Coal Gasification (CG) [57–59,62,63] are chosen as standard conventional processes. Other conventional, but less commonly used methods are: autothermal reforming [59,61], methane decomposition [59], or coal pyrolysis [57]. These processes are often compared to the additional downstream process of Carbon Capture and Storage (CCS) [59,61]. Considering hydrogen from Renewable Energy Sources (RES), analyses of alternative production pathways regard different water electrolysis processes [58,62,64]. In this context, various existing options for generating electricity are often taken into account.

Endpoint impact categories of the Life Cycle Impact Assessment (LCIA) are homogeneous across all environmental analyses, which can be explained by their comparable objectives. Ecosystem quality, climate change, human health, and resource scarcity are mentioned in most publications [59,61,62]. However, the considered midpoint impact categories vary due to different LCIA methods.

Differences between the individual analyses are evident when comparing their results. For example, Dufour et al. [59] conclude that CG, methane decomposition, and autothermal reforming are the most environmentally friendly conventional processes overall, when all impact categories are combined. Mehmeti et al. [62], on the other hand, identify CG as problematic, and also Liu and Liu [63] examine different CG processes as the fossil fuel concepts with the highest GHG emissions. The use of different LCIA methods can lead to widely varying results. Thus, the results of different studies can only be compared with difficulty, if at all.

The analyzed literature indicates that water electrolysis cannot be definitively classified as environmentally friendly or as harmful overall. Instead, the decisive factor is how the electricity is generated. If electrolysis is carried out with a conventional grid mix, its Global Warming Potential (GWP) is at the level of CG. If, however, electricity is generated via wind turbines or solar power, the GWP is lower than for almost any other process [58,62]. Another stream in the literature discusses the potential to reduce GHG emissions from fossil hydrogen production paths with CCS. Antonini et al. [61] identify GHG emission savings of 45–85 % for SMR or Auto Thermal Reforming and thereby classify the processes as comparable to alternative processes using renewable energy.

Although various studies have already examined the economic potential and environmental impact of FCEVs and BEVs, to our knowledge no study has yet included retrofitting in its scope of investigation. By including the conversion process of an HDV from an ICET into a FCET, our study aims to contribute to the existing literature and attempts to empirically integrate and examine the processes carried out in common practice from an economic and environmental perspective.

3. Methodology and data

3.1. Heavy-duty vehicle definition and research model

In Fig. 2 the research model is presented. The model is structured into three parts: The technical and general parameters (highlighted in yellow), the economic parameters (highlighted in blue) for the TCO

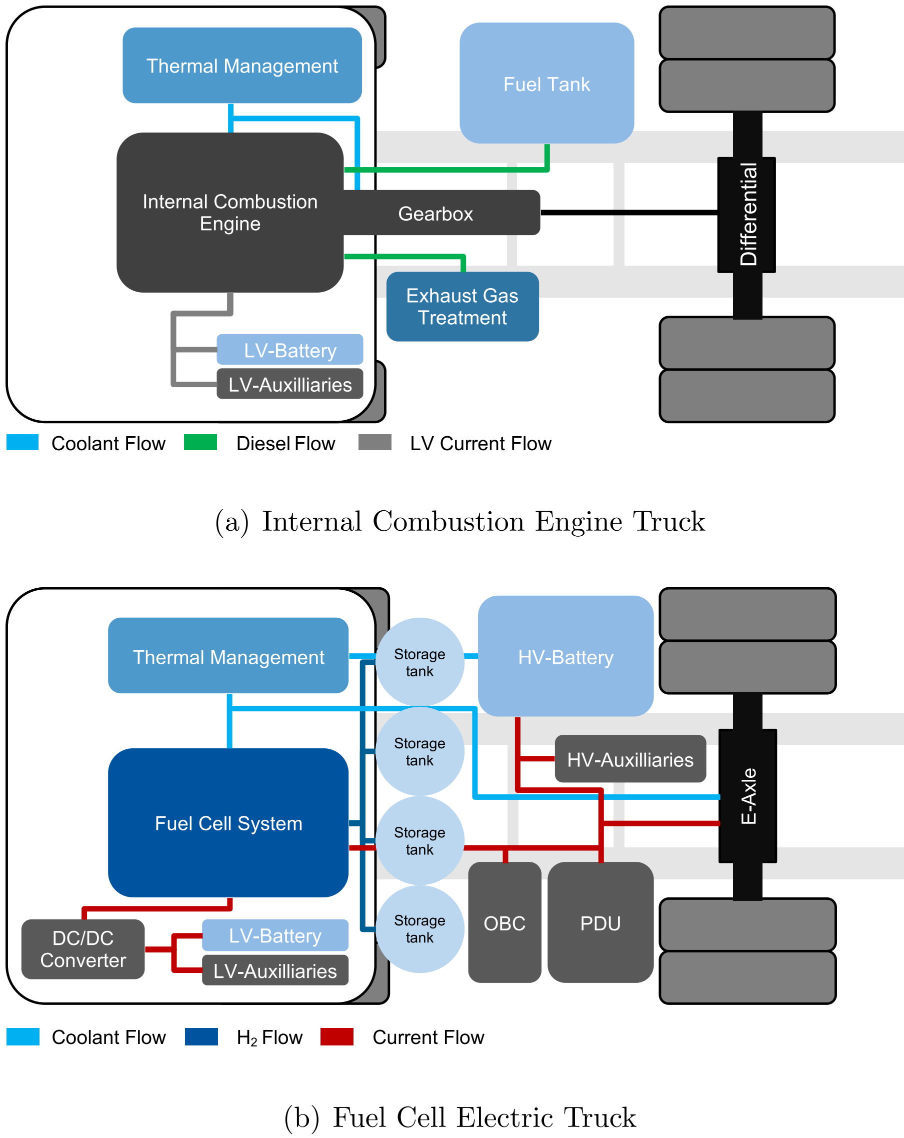

Fig. 3. Comparison of drivetrain topologies for internal combustion engine and fuel cell electric trucks; own illustration.

calculation and, finally, the environmental parameters (highlighted in green) for the LCA. In order to differentiate between data input and calculation, a dashed line (data input) and a solid line (calculation) indicate the type of parameter accordingly. In the following subsections, we describe all the parameters shown in Fig. 2.

For the analysis in this article, commercial vehicles of three different gross vehicle weights are considered. They all belong to the class of HDVs (in Germany: class N3) [65]. As pointed out in the introduction, this vehicle class has requirements regarding the energy system in terms of energy content and weight in order for such vehicles to fulfill their service, which makes the use of fuel cells necessary. The future application of fuel cell systems is not limited to the three vehicle classes considered in this article. However, given the current market situation, commercial vehicles of 18, 26, and 40 tons are the most discussed applications for fuel cell electric drivetrains [66].

Fig. 3 gives an overview of the vehicle architecture for both drivetrain concepts. Fig. 3 (a) shows the topology of an ICET. The combustion engine is fueled with diesel from the fuel tank and the chemical energy is converted to mechanical and thermal energy. For the mechanical output, a gearbox is attached to the engine and after passing through the differential, the mechanical energy drives the wheels. In order to dissipate the thermal energy, a thermal management system is necessary, which is connected to the combustion engine and the gearbox. A Low Voltage (LV) battery stores the electrical energy necessary for auxiliary units.

In contrast, the distinctive setup of an FCET is shown in Fig. 3 (b). The fuel cell system obtains hydrogen from the storage tanks and converts the chemical energy into electrical and thermal energy. The electrical energy is conducted towards the electric axle (e-axle) or the High Voltage (HV) battery via the Power Distribution Unit (PDU). The e-axle comprises an inverter, one or two electric motors, and the corresponding number of gearboxes in order to increase the overall efficiency of the vehicle. As an alternative to the e-axle, a central drive could be used as well. The HV-battery, also known as buffer storage, is used to equalize the load requirement of the truck and the available energy. The HV-battery is charged when the fuel cell output exceeds the required power and discharged vice versa. In addition, the HV-battery is charged by recuperation and optionally via an On-Board Charger (OBC). Depending on the voltage level of the fuel cell system, an additional converter is required. In order to dissipate the thermal energy, a well-specified thermal

Table 2
Component dimensions $P_{Component}$ of all subsystems for the fuel cell electric drivetrain for trucks of the considered weight classes [7,12,19,67].

Component	18 tons	26 tons	40 tons
Energy content HV battery [kWh]	50	71	145
Continuous power e-Axle [kW]	180	265	440
Power fuel cell system [kW]	100	140	240
Hydrogen capacity H_2 storage system [kg]	25	31	70
Thermal power thermal management [kW]	184	242	414
Electric power electric steering pump [kW]	9	9	9
Electric power electric air compressor [kW]	6	6	6
Charging power OBC [kW]	22	22	22
Electric power DC-DC-converter [kW]	180	265	440
Heating, Ventilation, and Air Conditioning (HVAC) [kW]	10	10	25
Power capacity PDU [kW]	180	265	440

management system is indispensable. Such a system typically consists of different circuits.

Table 2 lists the power and capacity of the individual components and systems for the three considered weight classes in this article. The values for the 26- and the 40-ton truck are the result of a comparison of announced FCETs [7,12,19,67]. Since there is currently no detailed announcement from the industry for an 18-ton FCET, the values for this vehicle are derived from conventional trucks or extrapolated from the higher weight classes.

3.2. TCO model

The TCO model developed in this article aims to determine the costs of one kilometer driven by a retrofitted HDV. Different vehicle ages at retrofitting and various scenarios may impact the TCO and thereby the costs per kilometer driven. We first calculate the TCO of the vehicle and then multiply it by the CRF to obtain a constant annuity valid for the time period considered. In combination with the average mileage driven per year, it yields a value for the TCO per kilometer in [€/km]. The term 'mileage' refers in this study to the distance driven in kilometers. In accordance with Noll et al. [29], Wu et al. [27], and Bubeck et al. [25], the TCO per kilometer is calculated as follows:

$$\frac{TCO_{Truck}}{km} = \frac{(CAPEX_{ICET} - \frac{RV_T}{(1+i)^T} + \sum_{t=1}^{T} \frac{OPEX_t}{(1+i)^t}) \cdot CRF}{\frac{1}{T}\sum_{t=1}^{T} VKT_t} \tag{1}$$

The purchase costs for the new diesel truck are included in $CAPEX_{ICET}$. The RV with a total vehicle lifetime T is discounted by the interest rate i. Unlike Noll et al. [29] or Wu et al. [27], in this article the discounted sum of the OPEX in each time period t is not averaged over the lifetime but multiplied by the CRF, as the CAPEX and the RV are. Hence, we prefer to refer to the approach used in Bubeck et al. [25]. This ensures the correct consideration of the time of expenditure. The resulting annuity is divided by the average VKT during the vehicle's entire lifetime. The CRF is determined as follows in accordance with Becker and Peppmeier [68]:

$$CRF = \frac{(1+i)^T \cdot i}{(1+i)^T - 1} \tag{2}$$

3.2.1. General parameters

In order to determine the TCO for an HDV, according to Eq. (1), some parameters have to be determined for the overall environment. We use the Weighted Average Cost of Capital (WACC) as a discount rate, since this value reflects the effective capital cost rate for a company active in a certain sector. The sector at hand is the transportation and logistics sector in Germany. We assume that the WACC is $i = 9.0$ %, as this is the best estimate to represent the cost of capital for this particular sector in May 2023 [69]. This discount rate recognizes the development in the financial markets during the past months and is realistic for the medium-term future. The value is in accordance with other studies on TCO analyses of heavy-duty trucks, such as Noll et al. [29] (7 %) or Basma et al. [30] (9.5 %).

For comparability of the results, it is necessary that all calculations refer to the same point in time. For this purpose, we set 2020 as reference year. All specific component costs are related to that year. To this end, component costs quoted in the literature in U.S. dollars are converted into Euros using the exchange rate of the year of publication and then referenced to 2020 using the appropriate inflation rate, unless the prices are already based on the 2020 technology level. The exchange rates and inflation rates used are provided in Table Appendix A.1 and Table Appendix A.2.

Finally, the annual mileage of the vehicles of different weight classes remains to be determined, as this is used in numerous cost items. In accordance with the literature [30] and official data from the German Federal Motor Transport Authority [70], this study assumes a degressive course of annual VKT over the vehicle lifetime. The degression is assumed to be the same for all three weight classes considered. Using the given data, the VKT for each source is determined as a percentage of the VKT of the original year. Subsequently, the values for both sources are averaged (see Table 3). The mileage in the first year is set for the individual weight classes according to Table 4. No distinction is made between the drivetrains considered, since we assume that fleet operators place the same requirements on FCETs as on conventional commercial vehicles. Furthermore, as described in Section 2.1, a truck is considered to be a new vehicle after retrofitting, which implies that we assume the mileage of a new conventionally driven truck for the first year of an FCET.

3.2.2. CAPEX

The capital expenditures include only the cost for the purchase of the conventional diesel truck in $t = 0$. We used the original prices without VAT from Deutsche Automobil Treuhand GmbH [71] and calculated the median of the original price for tractor units with a gross vehicle weight of 18 tons, 26 tons, and 40 tons. The data consist of 395 observations from three OEMs. In Table 4 the median values are listed under CAPEX.

3.2.3. Residual value

So far, the consideration of the RV of a commercial vehicle in the context of retrofitting with a fuel cell electric drivetrain has not been addressed in the literature. For the scope of this work, the valuation model of Kleiner and Friedrich [72] is applied. Although we have access to current resale values of HDVs [71], we cannot use them due to a lack of mileage data in the dataset. In order to estimate the resale value of an HDV, we therefore rely on the findings of Kleiner and Friedrich [72]. With their model it is possible to determine an RV based on the vehicle mileage, the drivetrain technology, and the GVWR. The equation for the evaluation of the residual value is adjusted to the following:

$$RV_{k,l} = 100 \cdot a_{k,l} \cdot e^{\frac{b_{k,l}}{\epsilon_l} \cdot VKT_{total,k,l}} \tag{3}$$

Table 3
Decrease in the annual vehicle kilometers traveled (VKT) [30,70].

Year of use	Percentage of initial VKT	Year of use	Percentage of initial VKT	Year of use	Percentage of initial VKT
1	100 %	6	77 %	11	45 %
2	100 %	7	75 %	12	43 %
3	96 %	8	63 %	13	42 %
4	88 %	9	61 %	14	40 %
5	85 %	10	47 %	15	38 %

Table 4
Initial VKT per weight class, CAPEX, residual value coefficients, and fuel consumption.

	18 tons	26 tons	40 tons	Source
VKT_0 [km]	60,000	95,000	115,000	[66,70]
$CAPEX_{ICET}$ [€]	139,420	163,443	169,312	[71]
$a_{k,l}$ [–]	0.833	0.88	0.951	[72]
$b_{k,l}$ [–]	−0.004	−0.003	−0.002	[72]
V_{Diesel} $[\frac{L}{100\ km}]$	27.1	27.6	30.8	[66,68]
V_{H2} $[\frac{kg_{H2}}{100\ km}]$	6.29	6.40	7.14	Own calculation

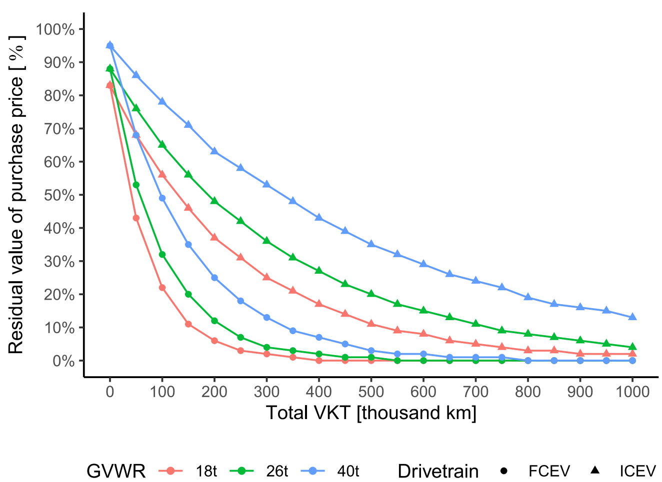

Fig. 4. Development of the residual value of heavy duty vehicles over their total lifetime in dependence of the weight class and the drivetrain technology; in accordance with Kleiner and Friedrich [72].

The outcome is the RV of the commercial vehicle in percent compared to the value at purchase. The coefficients $a_{k,l}$ and $b_{k,l}$ had been gathered empirically by Kleiner and Friedrich [72] and are shown in Table 4 with respect to the different Gross Vehicle Weight Ratings (GVWRs). The index k represents the GVWR, while the index l indicates the drivetrain technology.

The coefficient ε_{diesel} takes the technology maturity of the drivetrain and the density of the necessary infrastructure into account (see Fig. 4). For a diesel fueled internal combustion engine ε_{diesel} equals 1, as it is a mature technology with a high infrastructure density. We assume that the maturity and the infrastructure density of an FCET in 2022 are considered equal to those of a BET in 2017 ($\varepsilon_{k,FC} = 0.3$) [72].

The basis for calculating the RV of an FCET is the price of the vehicle retrofitting. Neither the RV of the glider without the conventional drivetrain is considered, nor the sale of the conventional drivetrain. Due to these assumptions, the relevant lifetime for calculating the RV is represented by the time the vehicle was used as an FCET. This is the period of time during which the fuel cell electric drivetrain was used, which is in line with the assumption of using the retrofitting costs as the basis for the RV determination.

The model of Kleiner and Friedrich [72] allows the RV to equal zero. With regard to the scrap value of the materials that a heavy-duty truck consists of, this assumption leaves room for improvement on a more realistic determination of the RV. Therefore, we include the scrap value of a truck at the end of its lifetime and set it as the lower bound for the RV, which is the net asset value. The Bill of Materials (BoM) from Wolff et al. [73] has been applied as the basis for the scrap value determination. The given masses for steel and metals are then multiplied by current scrap values in order to determine a scrap value for the entire vehicle. This also ensures that precious metals, such as platinum, are taken into account. However, we neglect any costs associated with recycling processes, since it is beyond the scope of our study. Scrap value data with material prices are based on values of material from the foreign trade balance provided by the Statistisches Bundesamt [74]. The (BoMs) are provided in Tables Appendix A.3 to Appendix A.6. The vehicle scrap values used in this study range from 6,105 € (18 tons) to 8,858 € (40 tons) for an FCET and 5,047 € for any considered ICET, in case it is not converted.

3.2.4. OPEX

The operational expenditures comprise the following items:

- Retrofitting costs
- Fuel costs
- Toll costs
- Service and maintenance costs
- Insurance costs
- Taxes

Cost items, such as personnel or administrative costs, are not taken into account, as these are incurred to the same extent in every case, regardless of the drivetrain, and are therefore irrelevant to the comparison of the retrofitting timings. One of the advantages of the fuel cell, compared to the battery electric drivetrain, is the possibility of short refueling periods, which are currently about 10 min per 15 kg_{H2} [75], but projections suggest that they might be equivalent to those of a diesel vehicle in the future [76–79]. With regard to current efficiencies and hydrogen storage capacities, the refueling can be conducted during mandatory driving breaks so that no additional time is necessary. In addition, authorities and suppliers work on advanced refueling protocols that allow higher mass flow rates. Therefore, we do not take additional time for recharging, and thereby personnel costs, into account for this article, which would, however, be necessary for the analysis of battery electric HDVs. This yields the OPEX per period as follows:

$$OPEX_{t,k,l} = C_{Retrofitting,t,k,l} + C_{Fuel,t,k,l} + C_{Toll,t,k,l} + C_{OM,t,k,l} + C_{Insurance,t,k,l} + C_{Tax,t,k,l} \quad (4)$$

Retrofitting costs

The costs of retrofitting the drivetrain are assigned to the operational expenditures, as the capital expenditures should only comprise expenditures at $t = 0$. The retrofitting costs are determined on the basis of the material costs. For each component relevant to the retrofitting, specific costs are gathered from the literature. All component costs are gathered from the average cost scenario of Kuhn et al. [80]. The specific component costs are listed in Table 5.

Based on these component costs and the vehicle-specific component data, the material costs for retrofitting are determined. According to

Table 5
Specific component costs for the retrofitting of a heavy duty vehicle from Kuhn et al. [80].

Component	Specific costs
HV battery	219.30 $\frac{€}{kWh}$
e-Axle	71.93 $\frac{€}{kW}$
FC system	1,096.49 $\frac{€}{kW}$
H_2 storage system	1,384.21 $\frac{€}{kg_{H2}}$
Thermal management	7.89 $\frac{€}{kW}$
Electric steering pump	263.16 $\frac{€}{kW}$
Electric air compressor	1,315.79 $\frac{€}{kW}$
OBC	63.16 $\frac{€}{kW}$
DC-DC-converter	78.95 $\frac{€}{kW}$
Heating, Ventilation, and Air Conditioning (HVAC)	127.19 $\frac{€}{kW}$
PDU	21.93 $\frac{€}{kW}$

Kuhn et al. [80], the material costs account for 87 % of the total vehicle manufacturing costs. These direct costs have to be combined with the indirect costs in order to ascertain the total retrofitting costs. One possible way to determine this total cost is by using an integration markup I_{markup}, which includes costs for research and development, marketing, insurance and assembly [81]. Considering all values given in the literature, this yields an overall markup integration factor of 1.40 (see Table Appendix A.9). In addition to that, we take assembly labor costs and other manufacturing costs into account, since they represent 13 % of the total vehicle manufacturing costs according to Kuhn et al. [80], Sharpe and Basma [81].

In order to facilitate the market entry of zero-emission HDVs, Germany had subsidized the retrofitting of vehicles until February 2024. Due to reasons of budget consolidation in the national budget of Germany and adherence to the debt brake, subsidies were recently removed. For that reason we assume that subsidies are no longer in effect; however, we still investigate in Section 4.5 how a reconsideration of subsidies would affect the results.

The conversion of conventionally driven trucks into FCETs was subsidized by the Federal Government with a share of 80 % of the retrofitting costs up to a certain threshold [82]. The maximum subsidy amount was 450,000 € for vehicles with a weight of 18 tons; 26-ton trucks were limited to 500,000 € and 40-ton trucks were limited to 550,000 € [82]. Therefore, for our sensitivity analyses we apply the same amount. Net retrofitting costs are thus calculated based on the following formula:

$$C_{Retrofitting,t,k,l} = \frac{\sum_{Components}(c_{Component} \cdot P_{Component})}{0.87} \cdot I_{markup} - Subsidy \quad (5)$$

Fuel costs

Fuel costs are determined based on Eq. (6) and are the product of the vehicle kilometers driven in the considered period VKT_t, the fuel consumption V_l, and the specific fuel costs c_l:

$$C_{Fuel,t,k,l} = VKT_t \cdot \frac{V_l}{100} \cdot c_l \quad (6)$$

The fuel consumption of conventionally driven trucks is determined based on reference values found in the literature and listed in Table 4. A complete summary with all considered values and the respective sources is provided in Table Appendix A.10. The hydrogen consumption of retrofitted HDVs is then determined via the chain of efficiencies in the vehicle, as described in Eq. (7). V_{Diesel} is the diesel consumption in $\frac{L}{100\ km}$. The specific energy contents for diesel and hydrogen are given as e_{Diesel} and e_{H2}, respectively, and amount to 9.8 $\frac{kWh}{L}$ for diesel and 33.33 $\frac{kWh}{kg}$ for hydrogen. In order to compare the fuel consumption, the efficiencies of both drivetrains are required and are established based on TTW efficiencies. TTW efficiencies $\eta_{TtW,Diesel}$ and $\eta_{TtW,FC}$ are determined to be 35.00 % for the diesel powered drivetrain and 44.37 % for the fuel cell electric topology [29,66,83]. The resulting hydrogen consumption is given in $\frac{kg_{H2}}{100\ km}$.

$$V_{H2} = \frac{V_{Diesel} \cdot e_{Diesel} \cdot \eta_{TTW,Diesel}}{\eta_{TTW,FC} \cdot e_{H2}} \quad (7)$$

Table 4 shows the fuel consumption for diesel and hydrogen depending on the vehicle weight. The specific fuel costs are the third parameter necessary to determine the fuel costs with Eq. (6). The price of one liter of diesel in Germany is gathered from the literature and is based on the average price during the first half of the year 2023. Table 6 comprises a list of specific costs for diesel and hydrogen used in this study. For diesel, only the scenario of purchasing fuel from the gas station at current market prices was considered.

Except for the on-site production of hydrogen, literature prices were used. The costs per kilogram of hydrogen produced on-site were determined similarly to a Levelized Cost of Energy (LCOE) approach. The Levelized Cost of Hydrogen (LCOH) is determined according to Eq. (8) and can be understood as a comparison of all costs incurred over the lifetime of the hydrogen production and the infrastructure facilities with the mass of hydrogen produced. We adjusted the equation in such a way that in addition to the costs, the mass of hydrogen produced is also discounted according to the maturity period. We discounted the mass of produced hydrogen, since revenues from the sale of the product can be implicitly taken into account (see, for example, Kost et al. [87]). Input data on the LCOH are provided in the appendix in Tables Appendix A.7 and Appendix A.8.

$$LCOH = \frac{CAPEX_{H2} + \sum_{t=0}^{T} \frac{OPEX_{H2,t}}{(1+i)^t}}{\sum_{t=0}^{T} \frac{m_{H2,t}}{(1+i)^t}} \quad (8)$$

Toll costs

HDVs of the weight classes considered are subject to a toll on federal highways and federal roads in Germany. The toll costs are calculated according to Eq. (9).

α_k indicates the share of the total annual mileage driven on toll roads as a function of the weight class. For this study, the values given in Table 7 were used. The value for the 40-ton truck is taken from the literature. For the other two weight classes, a share was assumed.

$$C_{Toll,t,k,l} = \alpha_k \cdot VKT_{k,t} \cdot c_{Toll,k,l} \quad (9)$$

$c_{Toll,k,l}$ describes the costs per kilometer of toll road in Eq. (9). They correspond to the values valid in Germany as of January 1, 2023 [88]. Since ZEVs, such as FCETs, are currently exempt from tolls, they are not included in the calculation for FCETs [30,90]. In addition, we have included toll costs from the draft of the third law amending toll regulations, which has been effective since December 1, 2023 and will include CO_2 toll costs for non-ZEVs [4]. Due to the unavailability of all values during the model's development, preliminary values from Trans.INFO [89] were used, which slightly differ from those that were recently published by official institutions. However, the difference from the officially published values is negligible. Table 7 provides an overview of the costs per kilometer of toll road in dependence on the weight class and the drivetrain technology.

Service and Maintenance costs

The costs for service and maintenance also scale directly with usage of the trucks. Given the expected mileage and the fact that service and maintenance can vary depending on the drivetrain, these costs can represent a significant portion of the operating costs. The costs for maintenance and repair are calculated as described in Eq. (10):

$$C_{OM,t,k,l} = VKT_{k,t} \cdot c_{OM,k,l} \quad (10)$$

Table 6
Specific fuel costs based on literature values.

Fuel	Production path	Abbreviation	Net fuel price	Source
Diesel	Gas station	Diesel	1.64 $\frac{€}{L}$	[84]
Hydrogen	On-site production with grid electricity	GEDEL	21.29 $\frac{€}{kg_{H2}}$	[13]
Hydrogen	H2Mobility fuel station	H2M	12.85 $\frac{€}{kg_{H2}}$	[85]
Hydrogen	Steam reforming with natural gas	SMR	1.04 $\frac{€}{kg_{H2}}$	[86]
Hydrogen	Coal gasification	CG	1.99 $\frac{€}{kg_{H2}}$	[86]
Hydrogen	Centralized Electrolysis with low-carbon electricity	LCECEL	4.92 $\frac{€}{kg_{H2}}$	[86]

Table 7
Shares of annual VKT driven on toll roads per weight class and costs per kilometer of toll road.

	18 tons	26 tons	40 tons	Source
α_k	0.5	0.7	0.8	Assumption; [30]
Conventional toll costs [$\frac{€}{km}$]	0.140	0.181	0.190	[88]
CO_2 toll costs [$\frac{€}{km}$]	0.100	0.124	0.158	[4]
$c_{Toll,k,Diesel}$ [$\frac{€}{km}$]	0.240	0.305	0.348	Own calculation
$c_{Toll,k,Diesel}$ [$\frac{€}{km}$]	0.238	0.313	0.348	[89]
$c_{Toll,k,FC}$ [$\frac{€}{km}$]	0	0	0	[90]

Table 8
Costs per kilometer for maintenance and repair in $\frac{€}{km}$.

Diesel			Fuel Cell			Source
18 ton	26 ton	40 ton	18 ton	26 ton	40 ton	
n/a	n/a	0.1577	n/a	n/a	0.1051	[91]
n/a	n/a	0.1773	n/a	n/a	n/a	[92]
0.1235	0.1238	0.1240	0.1100	0.1100	0.1100	[66]
n/a	n/a	0.1497	n/a	n/a	0.1925	[93]
n/a	0.0880	0.0880	n/a	0.0880	0.0880	[13]
n/a	0.1100	0.1100	n/a	n/a	n/a	[29]
0.1174	n/a	0.1675	0.0798	n/a	0.1174	[72]
0.1204	0.1100	**0.1240**	**0.0949**	**0.0990**	**0.1096**	MEDIAN
	0.1217					ADJUSTED

The costs per kilometer $C_{OM,t,k,l}$ were gathered from the literature and are summarized in Table 8. Maintenance and repair costs for 40-ton HDVs have been documented thoroughly. However, we found a lack of data in the literature for 18 tons and 26 tons. The finding that maintenance and repair costs for a diesel driven truck of 26 tons are below those for an 18-ton vehicle can only be explained by the use of different sources. In addition, the only study that considers both weight classes yields costs that increase with the vehicle weight. Therefore, the costs per kilometer for maintenance and repair were interpolated between the 18-ton and the 40-ton truck.

Insurance costs

In accordance with [29], the insurance costs are set to 2 % of the vehicle costs [29]. For the time that the vehicle is used as a conventionally powered truck, the vehicle's purchase costs form the basis for this determination. During operation as an FCET, the costs for the retrofitting are the input size for the calculation of the insurance costs, comparable to the determination of the RV.

Taxes

The annual vehicle taxes are costs that occur once per year and therefore are considered to be fixed costs. Tax costs depend on the weight and the drivetrain, but the considered vehicles are part of the highest tax class and, as a consequence, the taxes are the same for all the weight classes. For a diesel HDV, the vehicle taxes ($C_{Tax,t}$) amount to 556 € per year [94]. In order to assist the market penetration of alternatively propelled vehicles, HDVs with a fuel cell electric drivetrain are also exempt from vehicle taxes [95].

3.3. LCA model

3.3.1. Goal and scope of the life cycle assessment

The LCA in this study was conducted according to DIN 14040 and DIN 14044 [96,97]. The scope of our study is to provide findings on the environmental impact of retrofitting a commercial vehicle at different vehicle ages. The fundamental assumption is that HDVs should be retrofitted in order to achieve Germany's climate goals. Therefore, it is not our goal to compare different drivetrain topologies or to determine whether one technology is worth further development efforts. This question has been analyzed in several existing studies and has not yet been conclusively answered [50,52,53,98]. However, we want to address the question of the age at which an HDV should be converted, rather than whether it should be retrofitted at all.

In order to consider different scenarios for the hydrogen production, and thereby to recognize different developments in the hydrogen supply, our goal is to show the environmental impact of several synthesis pathways. The production of hydrogen via SMR is analyzed as well as water electrolysis. The results of the Life Cycle Inventory (LCI) including the emissions or the byproducts of the processes that are considered in the functional unit kg_{H2} constitute the input for the LCIA.

In contrast to other studies such as Yeow et al. [53] or Rial and Pérez [52], we limit ours to the fuel cycle and its conversion in the vehicle by applying a WTW analysis. Fig. 5 presents the processes considered

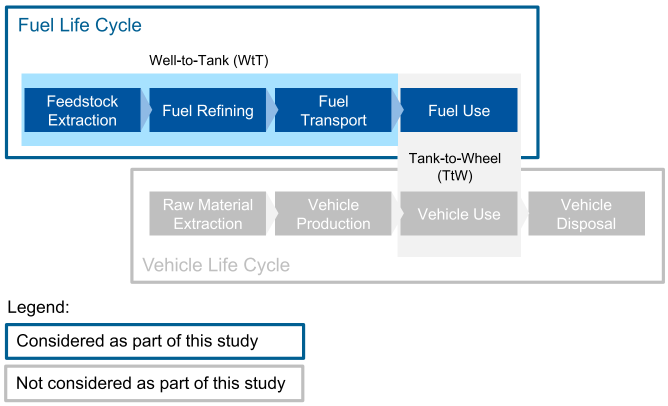

Fig. 5. Scope of the Life Cycle Assessment in this study compared to other studies; in accordance with Rial and Pérez [52].

in our analysis. The fuel is considered from the feedstock extraction, until its use in the vehicle and its reaction during energy conversion. Vehicle production, raw material extraction and return of new or used parts that can be reused or are refurbished, however, are not part of this study, since other studies suggest they are negligible [50] and have been covered already [50,51,56].

3.3.2. Life cycle inventory

For the LCI, inputs and outputs for each process step have been gathered from an extensive literature research. The first process step considered is the fuel production. Each process is then calculated with the software OpenLCA 1.11.0 by using data from ecoinvent 3.8 [99] (see Table Appendix A.14). Below, the analyzed fuel life cycles are explained in detail. Fuel cycles considered are: diesel for the time before retrofitting, the SMR as a conventional hydrogen production path, and the water electrolysis as representative of alternative hydrogen production.

Diesel Fuel Life Cycle

Due to limited evidence in the literature on the reaction products of the diesel combustion, we alter the approach of determining the environmental impact via OpenLCA calculations for the diesel fuel life cycle. Since reaction products are largely dependent on the operating conditions, the vehicle and the exhaust gas treatment have a major impact on the emissions. To our knowledge studies often only provide the LCIA results, but not the data used as inputs for the calculation. Therefore, the data for the LCIA of the diesel fuel life cycle are taken directly from the literature. The study by Rial and Pérez [52] delivers a holistic approach to the environmental impact of diesel fueled HDVs, including explicit results for the Well-To-Tank (WTT) and the TTW cycle.

Hydrogen Fuel Life Cycle

As part of the LCI of hydrogen, different fuel production pathways are analyzed. For the very large share of hydrogen produced from fossil fuels, the process of SMR with natural gas as fuel is considered. Alternative process routes are included in the form of production via water electrolysis in an alkaline electrolyzer.

For the SMR process, we refer to the process depicted in Nikolaidis and Poullikkas [100] and the ProBas process in Table Appendix A.11 from the Umweltbundesamt [101]. Subsequent to the production, the hydrogen has to be compressed in order to enable an economically feasible transportation. The energy for the compression is sourced from the electricity grid. The distribution of hydrogen is based on road transportation. In accordance with Kudoh and Ozawa [60], it is assumed that the transportation distance is 50 kilometers per way. With an assumed transport volume of 1000 kg of hydrogen per truck and a total weight of 19 tons for the corresponding truck, this yields an input of 1.9 $\frac{tkm}{kg_{H2}}$. In the final step of the WTT cycle, the fueling has to be considered. Electricity from the grid is the input for the compression to the necessary pressure level and for the fueling process itself. The output of the WTT cycle is related to 1 kg of fueled hydrogen (see Table Appendix A.11). The TTW cycle is similar for all hydrogen production paths, as this cycle is independent from the WTT path. The process for the release of the energy contained in hydrogen is the reaction in the vehicle's fuel cell. For mobile applications, Polymer Electrolyte Membrane (PEM) fuel cells are the dominant solution due to their dynamic characteristics. The reaction is given in Eq. (11):

$$2H_2 + O_2 \rightleftharpoons 2H_2O \tag{11}$$

Following the LCIA the energy output of this process is offset against the TTW efficiencies in order to ascertain the environmental impact per kilometer driven. The inputs and outputs for the LCI of the SMR production pathway are summarized in Table Appendix A.11 for the WTT-cycle and in Table Appendix A.12 for the TTW cycle.

An alternative path for the hydrogen production analyzed in this study is water electrolysis. As for the fuel cell, various technologies for electrolysis exist. As mentioned in Section 3.2, the technology considered here is Alkaline Electrolysis (AEL). The advantages are a high technological maturity and low operating costs. Since we also assume a constant electricity consumption, the AEL is the more appropriate technology for the purposes pursued in our study in comparison to Polymer Electrolyte Membrane Electrolysis (PEMEL). This is also in line with the considered use case. As the sustainable operation of a commercial vehicle depends on a constant fuel supply, the advantages of the dynamic operation pattern of a PEMEL depending on RES availability do not justify its usage against the AEL. The water electrolysis in the AEL follows the global reaction given in Eq. (12):

$$2H_2O \rightleftharpoons 2H_2 + O_2 \tag{12}$$

In order to comprehensively model the entire WTT cycle, additional infrastructure processes have to be considered. Here we use the AEL-based hydrogen production and the described processes from Gunawan and Monaghan [13].

Inputs and outputs of the AEL hydrogen production path of the WTT processes are given in Table Appendix A.13. We assume two scenarios for electricity production: On the one hand, the current grid mix in Germany and, on the other hand, electricity based on renewable energies. Again, we use data from ecoinvent (see Table Appendix A.14) to ascertain Life Cycle Inventories (LCIs) of the grid mixes [99]. The TTW cycle is the same as for the SMR.

3.3.3. Life cycle impact analysis

For the LCIA as part of an LCA, a method suitable for the goals and scope of the analysis has to be chosen. The task of this method is to transfer the results of the LCI into comparable indicators. DIN EN ISO 14044 is the standard for this procedure [96]. The way in which emissions are assigned to impact categories, their weighting factors, and the choice of which impact categories are taken into account, depends on the LCIA method chosen. In this study we use the ILCD 2011 Midpoint+ method. Retrofitting of HDVs should facilitate the reduction of GHG emissions, which are typically measured in $kg_{CO2,eq}$. Thus, climate change is set as a midpoint impact category. In addition, the chosen method is explicitly developed for the analysis of emissions into air, water, and soil, as well as the effects on human health and natural environment. Since ILCD 2011 Midpoint+ has been developed by the European Commission, it allows the environmental impacts relevant under European law to be measured. The use of ILCD 2011 Midpoint+ as a method is also consistent with methods in the literature, e.g., it has recently been used in other studies of LCA on HDVs, such as Rial and Pérez [52].

3.3.4. Interpretation

The interpretation of the LCIA results is conducted in Section 4.

Table 9
Scenario overview.

Scenario	Abbreviation	Comment
10 years usage	10 y	Assumed lifetime of long-haul truck with retrofitting
5 years usage	5 y	Average age of long-haul truck [103]
Variable usage as ICET and 5 years usage as FCET	$ICET_{Var} + FCET_{5y}$	Fixed usage of HDV after retrofitting

3.4. TCA model

In order to solve a potential conflict of objects, i.e., reducing the CO_2 emissions of heavy-duty transportation while not increasing the TCO, we apply the TCA approach, which combines both objectives.

In this study, the TCA implicitly calculates the expenses that must be taken into account to achieve a GHG emission reduction of one ton of CO_2. However, as Gillingham and Stock [102] already pointed out, so-called 'free lunch' options are potentially possible, which represent carbon reduction options without any cost.

Since companies would not invest in the retrofitting process of FCETs, if TCO and GHG emissions were higher, we assume that the difference between WTW emissions must be positive. Although it would be theoretically possible for corporations to disregard an increase in GHG emissions while decreasing the TCO, we opt not to consider this option. Calculating the TCO is only meaningful if any reduction in GHG emissions is accomplished. We therefore adopt the approach of Mojtaba Lajevardi et al. [39]. However, in contrast to them, we subtract the WTW emissions of FCETs from ICETs, as conducted by Gunawan and Monaghan [13]. In Eq. (13) the applied TCA calculation is presented:

$$TCA_t = \frac{TCO_{Truck,FC} - TCO_{Truck,ICE}}{WTW_{ICE} - WTW_{FC}} \tag{13}$$

where $WTW_{ICE} > WTW_{FC}$

4. Results and discussion

4.1. Scenario definitions

In order to allow statements on the impact of the retrofitting timing of HDVs with fuel cell electric drivetrains, various scenarios for different input factors are analyzed. Table 9 lists all scenarios considered in our study.

In scenarios 10 y and 5 y, the time of operation as a conventional ICET is varied, which also implies a varying operation time as an FCET. The TCO per kilometer is displayed over the time of vehicle operation as a conventional ICET. For the remainder of its total assumed lifetime, the truck is operating as an FCET. In contrast, scenario $ICET_{Var} + FCET_{5y}$ has a variable duration of the operation period as an ICET and a fixed

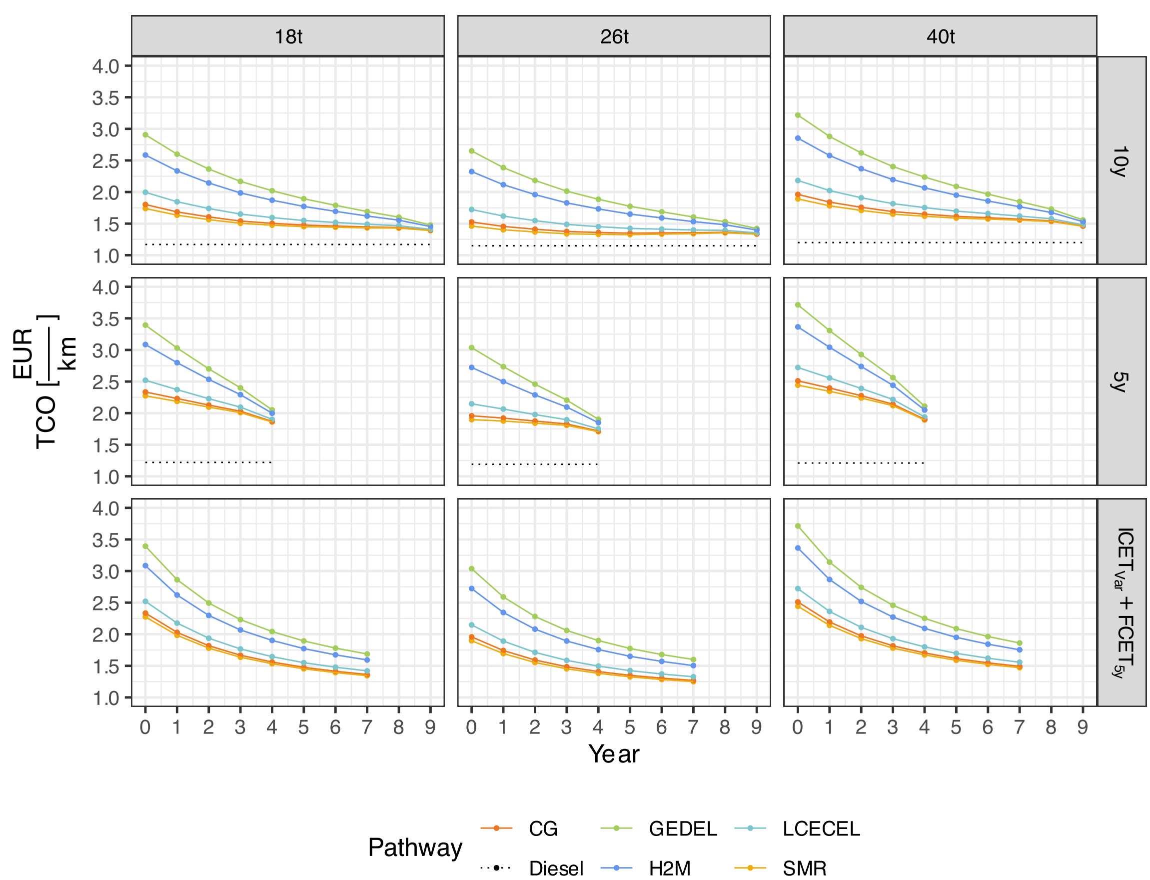

Fig. 6. TCO per km for different scenarios and production paths with varying retrofitting dates.

lifetime as a retrofitted FCET of 5 years. In this case, the total lifetime of one vehicle varies between five and twelve years, because after being used for seven years as one drivetrain, the percentage of the initial VKT drops below 75 %, as shown in Table 3. The earliest opportunity for retrofitting is immediately before the start of use, which is regarded as year 0. The latest conversion occurs in the penultimate year, so that the vehicle is operated as an FCET for at least one year. A purely diesel-fueled operation is also considered, but only for a general comparison and not to answer the question of whether retrofitting itself is economically reasonable. An exception to this will be the scenario $ICET_{Var} + FCET_{5y}$.

4.2. Total cost of ownership

Fig. 6 shows the TCO for all weight classes, pathways, and scenarios considered. In the horizontal boxes, the presented scenarios are depicted. The dotted line shows the reference scenario as the case if no retrofitting is conducted. All other pathways assume that the vehicle is retrofitted. Each year of retrofitting is indicated on the x-axis.

Our results suggest that in almost all cases the TCO per kilometer is lower, the more years the HDV is operated conventionally, and — conversely — the fewer years it is operated with hydrogen. The earlier a vehicle is retrofitted, the more the results diverge, which is mainly due to the fuel price and the effect of the interest rate.

If the truck is retrofitted immediately after purchase, the TCO can differ substantially. In the case of pathway Grid Electricity Decentralized Electrolysis (GEDEL) and 10 y ownership, the TCO ranges between 2.65 $\frac{€}{km}$ (26t) and 3.22 $\frac{€}{km}$ (40t). Pathway H2Mobility (H2M) yields a similar finding. With a rather high TCO of 2.32 $\frac{€}{km}$ (26t, Year 0) and 2.85 $\frac{€}{km}$ (40t, Year 0), the costs constantly decrease as the retrofitting time changes. Shifting the retrofitting time to five years later, the TCO can be reduced by approximately 46 % (GEDEL) and 52 % (H2M). The Low-Carbon Electricity Centralized Electrolysis (LCECEL) scenario shows that it also has a higher TCO than the reference scenario for a total lifetime of 10 years, where no retrofitting occurs. Our results show that none of the pathways with electrolytically produced hydrogen represent feasible ways to reduce TCO or at least are an equally good option economically.

Yet even the fossil pathways SMR and CG show a higher TCO with about 1.46 $\frac{€}{km}$ (26t, Year 0) and 1.53 $\frac{€}{km}$ (26t, Year 0), indicating that even the lowest costs are not competitive with ICETs. However, this strongly depends on the GVWR and the ownership period taken into account. These results are slightly higher than those from Mojtaba Lajevardi et al. [39], which are about 1.2 $\frac{\$}{km}$ in their low-carbon scenario and 0.9 $\frac{\$}{km}$ in their high-carbon scenario for a parallel hybrid fuel cell vehicle on average. Results from Gunawan and Monaghan [13] of 1.0 $\frac{€}{km}$ (on-grid) and 1.6 $\frac{€}{km}$ (off-grid) tend to be comparable to the LCECEL (2.18 $\frac{€}{km}$) and GEDEL (3.22 $\frac{€}{km}$), although our results are more than twice as high.

In 10-year ownership scenarios, the results also depend on the GVWR of each truck. While 18t and 40t HDVs tend to have decreasing Total Cost of Ownerships (TCOs) in all scenarios, the fossil pathways with 26t HDVs exhibit an optimum TCO in year 5. However, overall, the difference between scenarios LCECEL, SMR, CG, GEDEL, and H2M shows

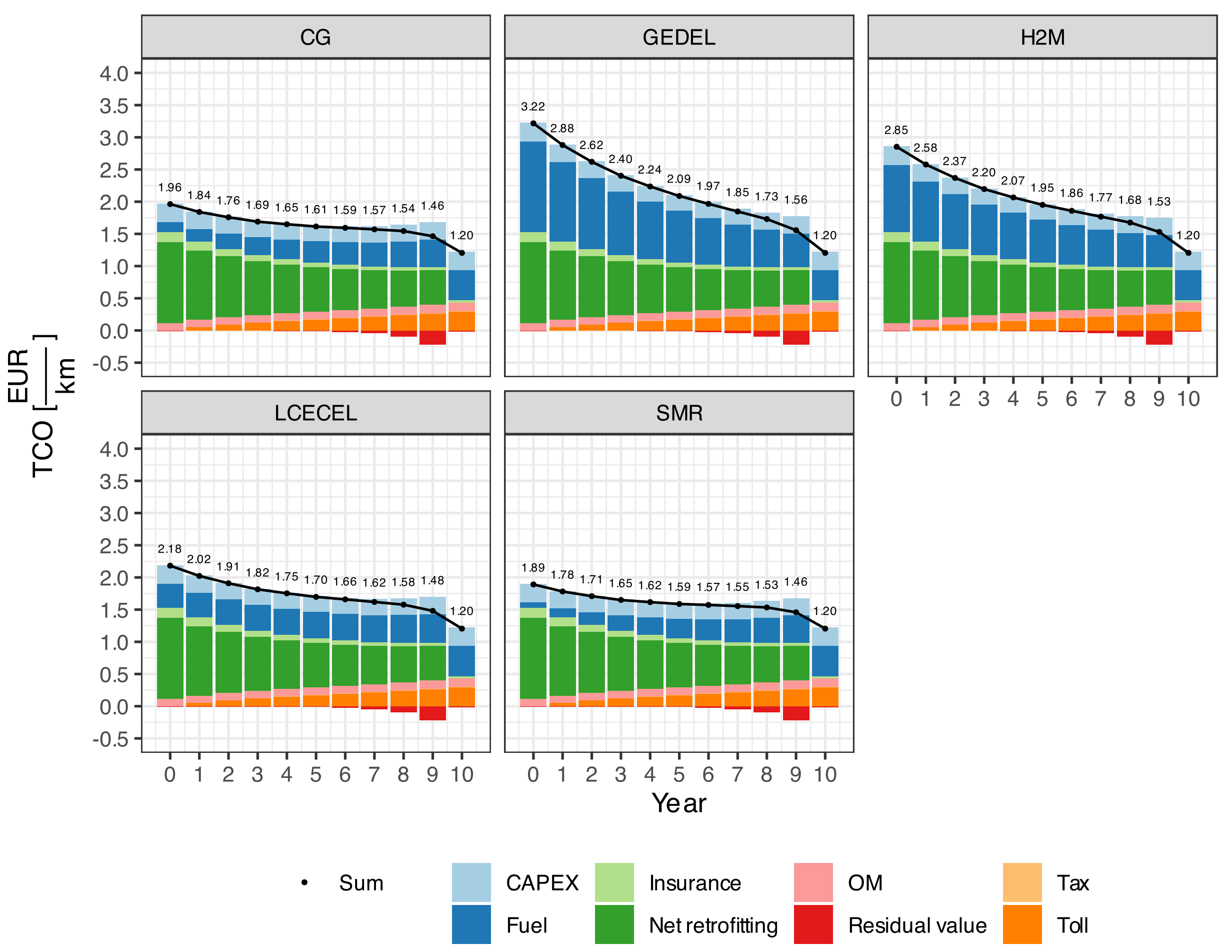

Fig. 7. TCO per km for 40t and 10 year scenarios structured by cost category and hydrogen production pathway.

the enormous effect of hydrogen prices on the economic performance of retrofitting, especially in the first years.

According to our results, the ownership period is another crucial parameter for economic attractiveness when retrofitting timing is considered (see Fig. 6). The 5 y scenario shows that cost reduction potential is even more apparent. On average, the TCO was 76 % (GEDEL) and 64 % (H2M) lower after only 4 years. Unlike the most costly pathways (GEDEL and H2M), this effect is attenuated for the other paths but is still present. These results demonstrate that even the most economic FCET pathways are not an option to incentivize the retrofitting for freight forwarders, as ICETs are currently still more cost-efficient than any of the investigated pathways with FCETs.

In contrast, the pathways for the 5 y scenario generally perform substantially worse than their counterparts in the 10 y scenario. This result emphasizes the need for a longer ownership period to reduce and distribute retrofitting costs over the ownership period.

Finally, the $ICET_{Var} + FCET_{5y}$ scenario underlines the general trend that longer ownership periods as an ICET decrease the TCO. However, it can be seen that scenarios GEDEL and H2M benefit the most from longer usage as an ICET, as opposed to SMR and CG (26t). Hence, we show that it pays off to retrofit later from an economic perspective, especially for high-fuel-cost scenarios such as GEDEL and H2M.

As mentioned above, in the 10 y (Retrofitting year 9) and 5 y (Retrofitting year 4) scenarios the penultimate year shows a substantial drop in terms of costs. This decrease is undoubtedly due to the residual value of the vehicle, as the vehicle is only used for one year so that high retrofitting costs and low mileage as an FCET contribute to that.

Fig. 7 shows the distribution of cost categories for a 40t truck in the 10 y scenario (top right in Fig. 6). The previously mentioned residual value effect in the penultimate year can be observed quite clearly. Fuel costs and net retrofitting costs are apparently the major contributors in most cases.

In the GEDEL scenario, fuel costs range between 33.79 % (Year 9) and 43.65 % (Year 0), while in the SMR scenario fuel costs are between 4.12 % and 29.33 %.

Net retrofitting costs do not change from pathway to pathway but can strongly influence total costs due to the fact that no subsidies are granted. In the GEDEL scenario, net retrofitting costs are rather consistent over all retrofitting years with values between 34.73 % (Year 9) and 38.96 % (Year 0). In contrast, with SMR, values range from 37.07 % (Year 9) to 66.29 % (Year 0). LCECEL shows a more balanced distribution of fuel costs over all potential retrofitting years, since in this pathway the annual fuel costs are similarly independent of the drivetrain technology. This underlines again the importance of retrofitting costs for the TCO when operating HDV fleets.

Besides the major impact of fuel costs in all pathways, it is apparent that toll costs are increasing remarkably, so that they will have a considerable effect on total costs for late retrofitting periods. Over all pathways the toll costs can constitute between 1.64 % and 18.09 % of total costs in the penultimate year, which underlines the efficacy of the toll regulations established by the Bundesministerium für Digitales und Verkehr [4]. In contrast, insurance and net retrofitting costs become less important with later retrofitting periods in absolute terms, because discounting affects those strongly.

In contrast to earlier findings of Alonso-Villar et al. [14], we find a substantially lower absolute TCO of about 2.02 million € (40t, 15 year

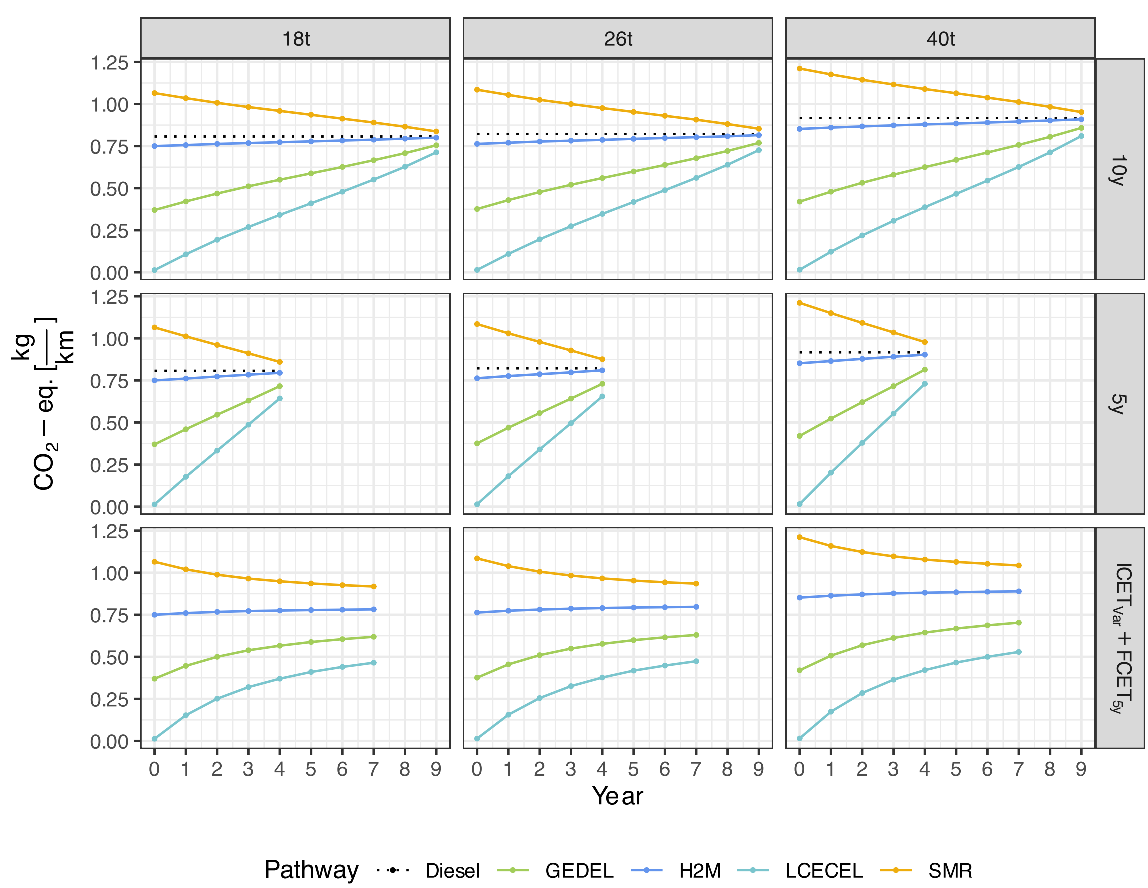

Fig. 8. GWP for different scenarios and production paths with varying retrofitting dates.

ownership, only fuel cell, GEDEL) in comparison to approximately 2.7 million \$ (12–40t, 15 year ownership, only fuel cell) of Alonso-Villar et al. [14].

4.3. Environmental impact of heavy-duty vehicle retrofitting

As described in Fig. 2, we present two LCA impact categories: climate change (Indicator: GWP) and particulate matter (Indicator: $PM_{2.5}$). Fig. 8 shows the results of the GWP for the previously presented scenarios. Due to lack of data in other hydrogen production paths and lower relevance, we only consider GEDEL, SMR, LCECEL, and H2M as the most relevant pathways and leave out the CG pathway.

Results show that in the 10 y and 5 y scenarios and all pathways, the CO_2 emissions either increase (GEDEL, H2M, LCECEL) or decrease (SMR) linearly. SMR shows the highest emission output with about 1.21 $\frac{kgCO_2-eq.}{km}$ (40t; 5 y, 10 y and $ICET_{Var} + FCET_{5y}$) for immediate retrofitting. For the same year, the GHG emissions of the LCECEL pathway are hardly noticeable with 0.02 $\frac{kgCO_2-eq.}{km}$. The most striking result to emerge from Fig. 8 is the H2M scenario, which has an RES share of 30 % and a hydrogen production share with an SMR of 70 % [104]. It performs hardly any better than the reference scenario, which underlines the importance of the GHG reduction potential of RES.

Overall, these results suggest that SMR should be avoided if the primary goal is to reduce GHG emissions, while GEDEL, H2M, and LCECEL can be utilized to decrease GHG emissions but with a different intensities from that of the reference scenario. Furthermore, early retrofitting dates are most likely the better choice for most pathways in terms of reducing GHG emissions over the vehicle's lifetime, especially pathways that are supplied by RES.

Slightly different statements can be made regarding the behavior of $PM_{2.5}$. Fig. 9 presents our results for the $PM_{2.5}$ emissions. SMR has emissions that are approximately 72.78 % higher than the reference scenario in comparison to H2M emissions exceeding the reference scenario by 32.04 % (Year 0). Another striking result is the emissions of $PM_{2.5}$ in the H2M pathway, which are noticeably above the reference scenario. Thus, whereas the H2M pathway shows an improvement over conventionally driven HDVs in terms of GHG emissions reduction, for $PM_{2.5}$ one can observe that the H2M pathway performs worse than the reference scenario. In year 0, $PM_{2.5}$ emissions are between 1.18 $\frac{g\,PM_{2.5}-eq.}{km}$ (18t) and 1.34 $\frac{g\,PM_{2.5}-eq.}{km}$ (40t), which is on average approximately 25.77 % over the reference scenario for each GVWR.

The RES pathway GEDEL demonstrates even better results in comparison to the results from Fig. 8. $PM_{2.5}$ emissions are between 0.40 $\frac{g\,PM_{2.5}-eq.}{km}$ (18t, Year 0) and 0.45 $\frac{g\,PM_{2.5}-eq.}{km}$ (40t, Year 0). This results in 57.54 % lower $PM_{2.5}$ emissions than in the reference scenario. However, it has to be remarked that $PM_{2.5}$ is emitted locally at the SMR plant, where hydrogen is produced. For the reference scenario, $PM_{2.5}$ is much more dispersed over the itinerary of the ICET, so that environmental effects might be more severe [105].

4.4. Carbon abatement costs

To effectively assess the potential to reduce carbon emissions per costs incurred, we employ the TCA method. Since the motivation for retrofitting is to switch to a more sustainable vehicle than before, it is

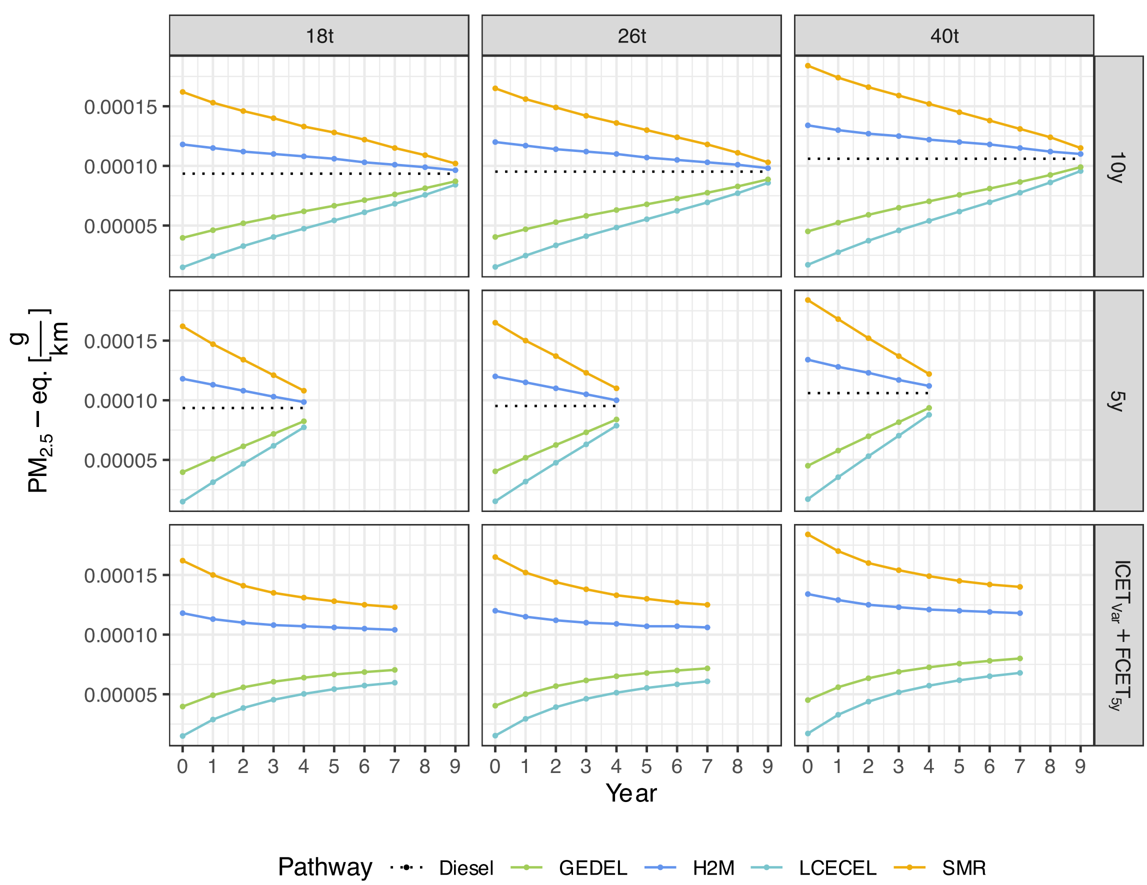

Fig. 9. $PM_{2.5}$ for different scenarios and production paths with varying retrofitting dates.

consequently necessary that the retrofitted HDV has a positive environmental impact in relation to the status quo in order to obtain reasonable results. Therefore, we only include pathways that feature GHG emission reduction (i.e. GEDEL, H2M, and LCECEL) as defined in Eq. (13).

Fig. 10 reveals the relationship between assessed costs by the TCO and saved tons of CO_2 determined by the LCA in $\frac{€}{t\,CO_2}$. Unlike the figures before, the columns contain the scenarios and the rows contain the pathways described above. Since the results of the TCA have significant divergence, we freely scale the y-axis.

First, the results show that almost all curves have a U-shaped trend over all potential retrofitting periods in the 10 y scenario. This is due to the fact that the economic disadvantage diminishes, while the benefit of saved GHG emissions declines at even faster rates for late retrofitting periods in comparison to the cost reduction. This leads to favorable retrofitting timings in later periods. Although this trend is less pronounced in the LCECEL pathway, as the TCO does not decrease as substantially as in the other pathways over all considered periods, and only the diminishing CO_2 benefits affect the resulting TCA. The penultimate year also demonstrates the strong effect of the residual value impacting the TCA in such a way that we obtain the highest TCA values in all pathways in the 10 y scenario and 5 y scenarios.

Second, it can be observed that results are rather diverse and that they highly depend on each pathway. While the minimum of TCA for a 40t HDV of GEDEL lies at around 3,535 $\frac{€}{t\,CO_2}$ in $t = 0$, it is around 22,540 $\frac{€}{t\,CO_2}$ in the H2M pathway and at around 1,000 $\frac{€}{t\,CO_2}$ in the LCECEL pathway. For the costs incurred, the GHG emission reduction potential in the H2M and the GEDEL pathway is not competitive at all. But even in the LCECEL scenario, the TCA increases in later periods substantially, suggesting that none of the non-fossil pathways are viable pathways with current costs and GHG emissions. Yet, in the $ICET_{Var} + FCET_{5y}$, a clear trend is visible that TCA can be reduced when extending the vehicle's time as an ICET. This applies to all GVWRs and pathways.

Our results emphasize again the demand for affordable hydrogen, while ensuring substantial GHG emission reduction potential. Although the H2M pathway has 30 % RES energy, the TCA turns out to be enormously high at current price levels. However, the GEDEL pathway is also not able to reduce the TCA, since the results indicate that GEDEL has the highest TCO of all pathways. Even noticeable GHG emission reductions are not capable of compensating for such high costs.

Third, the 5 y scenario shows generally higher and even more sharply rising TCA values. Hence, according to our results, the shorter the ownership period, the more beneficial early retrofitting periods seem to be, particularly if the TCO is below 1.4 $\frac{€}{km}$.

Results from Mojtaba Lajevardi et al. [39] are slightly lower than ours at just above 500 $\frac{\$}{t\,CO_2}$ in the low-carbon scenario. However, their study results reveal a higher TCO in the reference scenario and a lower TCO for the FCETs, while our GHG emission results are lower compared to their finding. According to Gunawan and Monaghan [13], the TCA for on-grid water electrolysis ranges from 100 to 600 $\frac{€}{t\,CO_2}$, while off-grid electrolysis incurs costs between 900 and 1,250 $\frac{€}{t\,CO_2}$ in dependence on different carbon taxes. Since we have included an indirect carbon tax from the toll regulations of about 200 $\frac{€}{t\,CO_2}$, our results of approximately 1,000 $\frac{€}{t\,CO_2}$ are above those of Gunawan and Monaghan [13], but still in a similar range.

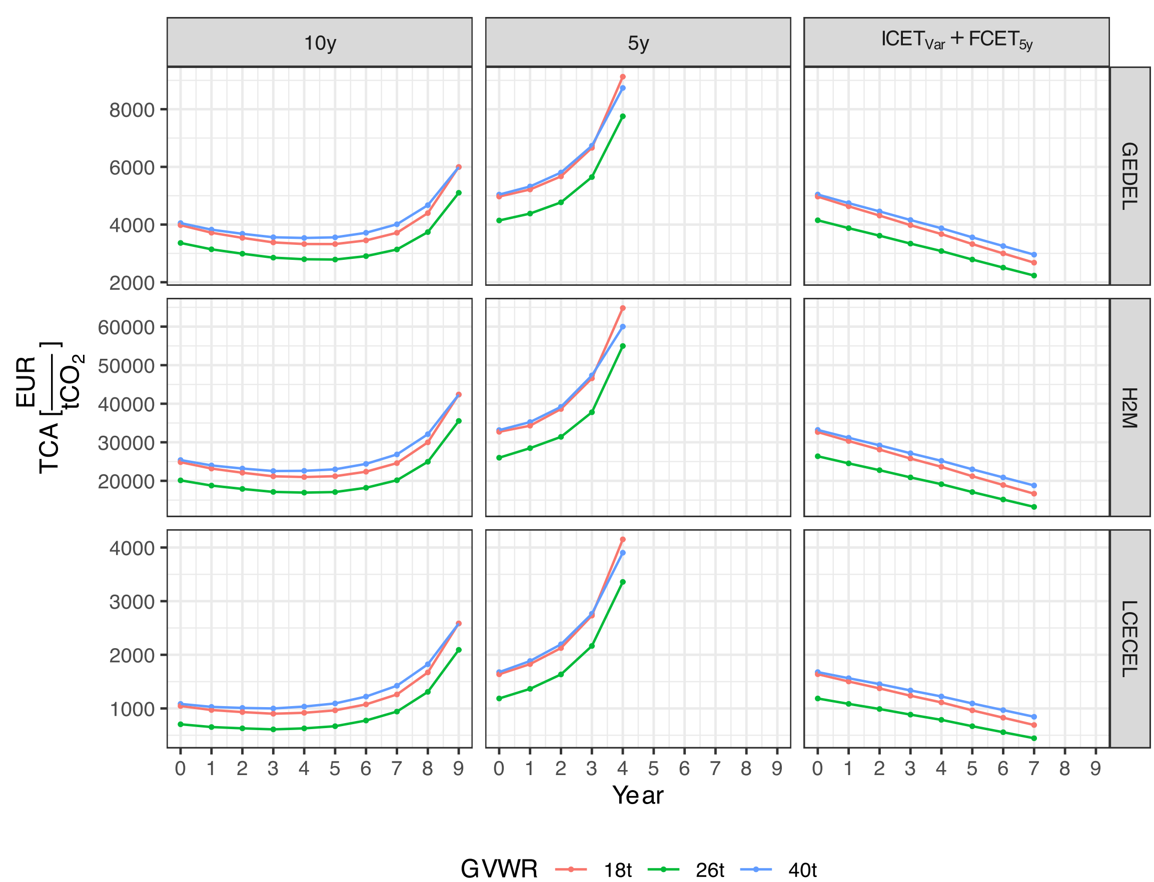

Fig. 10. TCA for different scenarios and production paths with varying retrofitting dates.

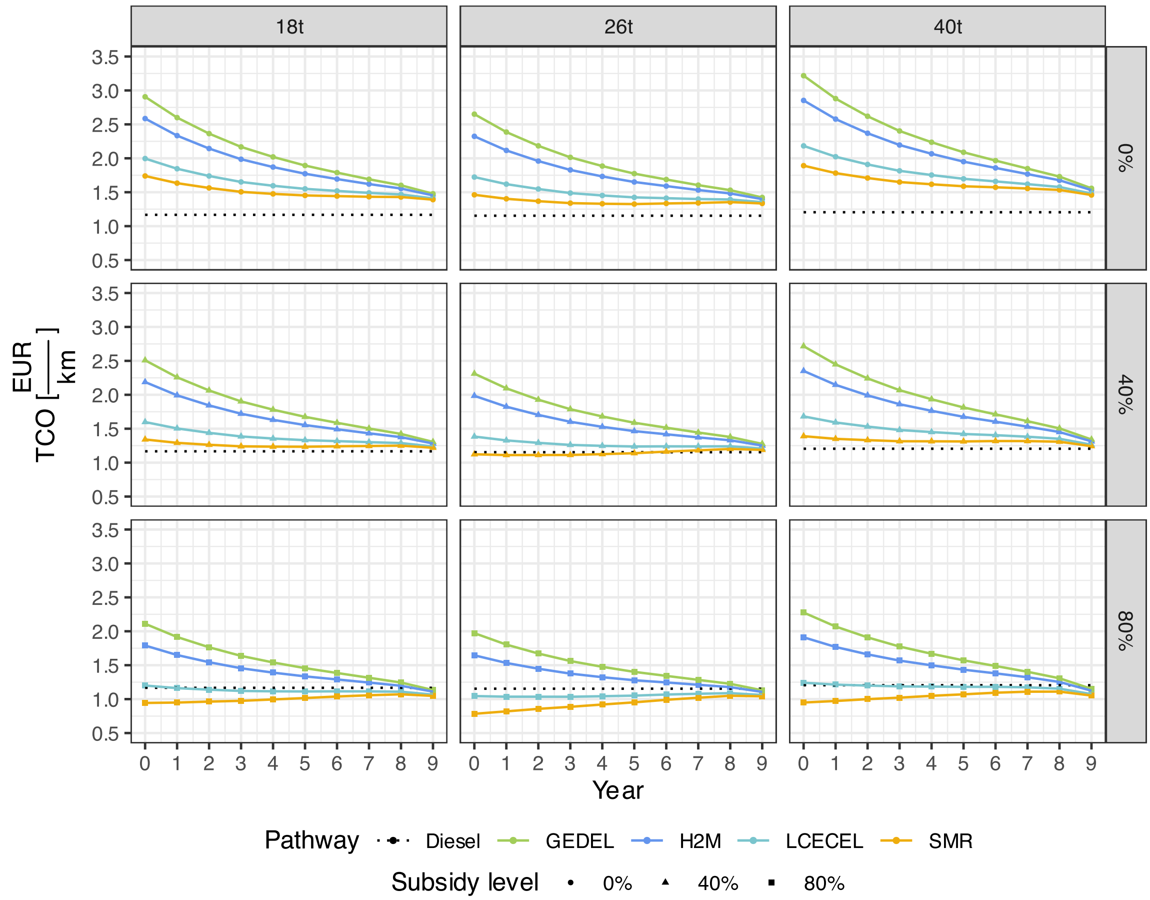

Fig. 11. TCO with different subsidy levels.

4.5. Sensitivity analysis and impact of subsidies

As mentioned in previous sections, subsidies might have a significant impact on the TCO and therefore on the economic attractiveness to customers. In Figs. 11 and 12, the impact of different subsidy levels (0 %;40 %;80 % as reference) is shown.

What is striking in Fig. 11 is that the U-shaped trend becomes more moderate at 40 % subsidies and then declines at 80 % subsidies. With 80 % subsidies, only the LCECEL path of the 26t truck is below the reference over all time periods. From year 2 onward and at an 80 % subsidy level, almost all values of the TCA in the 10-year scenario for the LCECEL pathway are negative, representing low-hanging-fruit opportunities, since the TCO is below the conventional drivetrain, and CO_2 reduction can be achieved easily. In contrast, the H2M and GEDEL pathways do not come close at all. These findings underline the need for subsidies to bring retrofitted FCETs towards TCO parity.

The TCA highlights how effective a higher subsidy level can be in reducing the cost per $t\,CO_2$ saved. It can be seen that a subsidy increase of 40 percentage points can reduce the TCA by 50 %. Especially for lower subsidy levels (0 % and 40 %), the optimal retrofitting period tends to be between year 3 and year 5. The later the period, the more the TCA values diverge. For an 80 % subsidy level, the optimal retrofitting period is always in year 9.

Fig. 13 shows the impact of various model parameters on the TCO by increasing (reducing) the input value by 15 % (−15 %). For all GVWR categories, the mileage and retrofitting costs reveal the greatest impact on the TCO. While for 18t retrofitted HDVs, the impact of annually driven kilometers has the highest impact, the effect slightly recedes for 26t and 40t. In addition, for 18t and 40t HDVs a change in retrofitting costs especially affects the TCO. On top of that, our results reveal that the importance of purchase costs diminishes when higher GVWRs are taken into account. An increase or decrease in the integration markup shows roughly the same effect as the retrofitting costs. Based on the findings of Sharpe and Basma [81], it is expected that the integration markup will subside in the next few years.

4.6. Recommendations for industry and policymakers

In the previous sections we have presented our results in order to answer our proposed research questions from Section 1. These results have shown that the optimal retrofitting age of a vehicle can depend on a wide variety of factors, such as residual value, total lifetime, retrofitting costs, and subsidies, although the net retrofitting costs and the type of hydrogen production can certainly be identified as the most influential parameters for the TCO and LCA. Results for the TCA emphasize the necessity of a low carbon and reasonably priced hydrogen production with a moderate to high subsidy level to ensure that investments in FCET fleets are worthwhile in terms of maintaining everyday operations and reducing fleet emissions. Hence, the above presented results leave

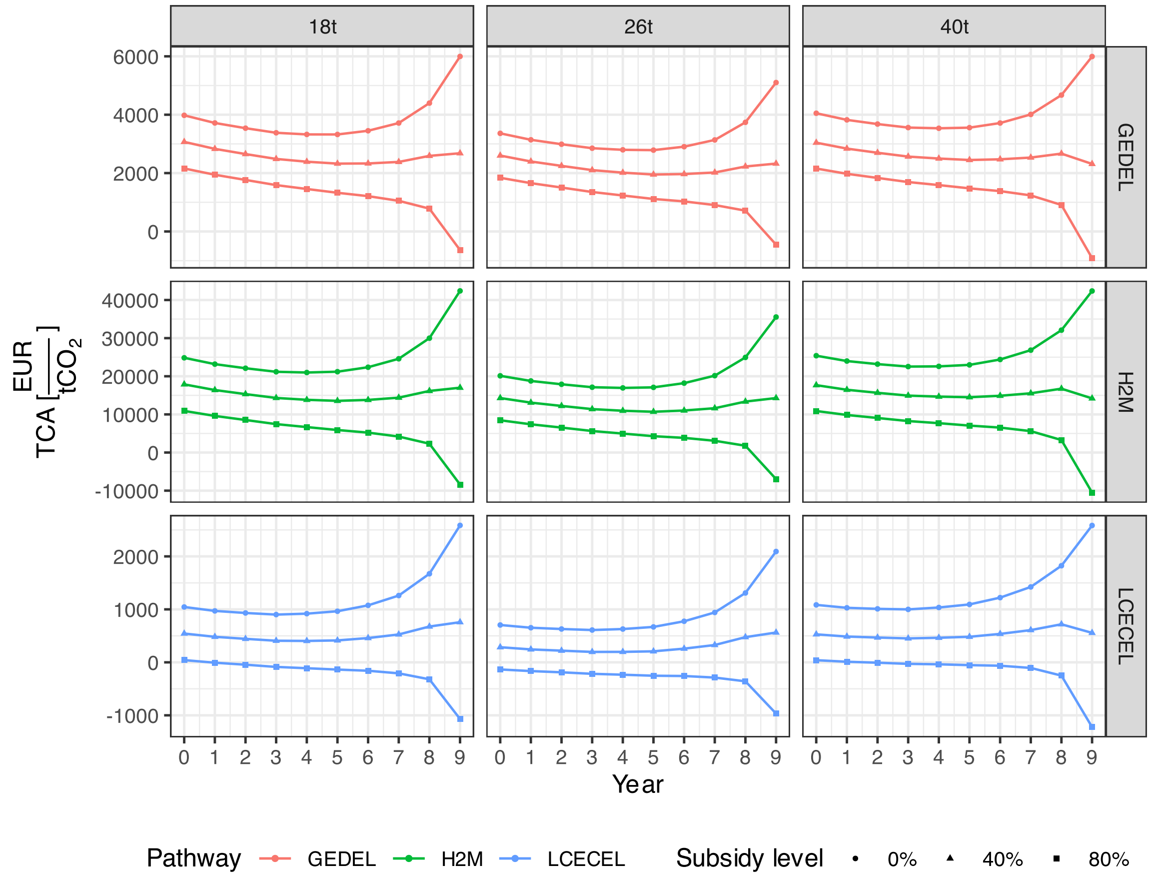

Fig. 12. TCA with different subsidy levels.

room for discussion on what measures must be adopted by policymakers and how freight forwarders should make a decision about whether to retrofit.

With current costs and without any subsidies, retrofitting is not worthwhile for fleet operators at the moment. Every considered pathway showed a higher TCO than the diesel reference. This applies even for the fossil pathways, which have considerably lower fuel costs than the others. Ultimately, the retrofitting costs simply represent a too heavy burden on the total costs in order for retrofitted vehicles to be a viable alternative to ICETs.

However, we have also demonstrated in the sensitivity analysis that retrofitting can lead to significant economic and environmental benefits with global average renewable LCOH of 4.92 $\frac{€}{kg\ H_2}$ [86] if medium to high subsidy levels are taken into account. Although, it is important to note that additional costs, such as distribution, storage, and refueling, are not taken into account by that price. As a pump price of 4.92 $\frac{€}{kg\ H_2}$ is currently not available, this scenario can be considered an indicator of the consequences of a pump price of around 5 $\frac{€}{kg\ H_2}$.

Subsidies play a major role here by making retrofitting more compelling. Since the German government subsidized retrofitting fairly highly with up to 550,000 €, we recommend that subsidizing should be continued until market diffusion of FCETs has reached a certain threshold. Otherwise, FCETs are clearly not competitive enough at current prices. In order to further foster the retrofitting process of FCETs, it should therefore be clearly communicated whether and how subsidies will be distributed in the upcoming years. A potential approach could be, first, a renewal of a moderate subsidy level and, afterwards, a stepwise reduction of subsidies, as proposed by the German Energy Agency [106].

Fig. 14 shows a potential path for reducing subsidies when including technological progress and the associated cost reductions of fuel cells, hydrogen storage and hydrogen based on the H2M scenario with a five year operation as FCET with data and results from Burke et al. [34] and Link et al. [107]. The following factors were not taken into account in this analysis: an increase in powertrain efficiencies, price reductions in other electric vehicle components, carbon taxes, or rising diesel fuel costs. In order to maintain a competitive price point for fleet operators, it is necessary to provide subsidies at a rate of 80 % when considering the reference scenario. The anticipated cost reductions in literature scenarios for 2025 suggest the possibility of reducing subsidies five years later, resulting in a net cost reduction for fleet operators. This indicates that the offset by technological progress is more substantial than the amount of subsidy reduction. However, a further reduction to 0 % over the course of five years shows a substantial increase in net costs for operators. This is due to the fact that technological progress and scaling effects do not keep pace with subsidy reduction in the 2030 cost scenario. In the case that the reduction of subsidies should be aligned with the technological progress, it is recommended that subsidies be reduced to 27 % in 2025 and 14 % in 2030. In the year 2035, the necessity for subsidies will likely be reduced to 2 %, thus allowing for the potential cancellation of their payment. Yet, this still does not ensure that FCETs are economically competitive with ICETs. We have calculated 5-year net costs for the operation of an ICET of 507,039 €. Achieving price parity

Fig. 13. Sensitivity analysis.

would therefore require a reduction in subsidies to approximately 54 % in 2025, 42 % in 2030, 31 % in 2035, and 24 % in 2040. Consequently, to ensure the competitiveness of FCETs an extension of subsidy payments is required. The cost scenarios under consideration for 2025 and 2030 are based on literature data. The probability of occurrence of these scenarios can be discussed.

A direct comparison of purchase costs reveals that the acquisition of a new FCET is more cost-effective. This is due to the fact that the total manufacturing efforts are lower in this scenario and the material costs are equivalent. A review of the literature suggests that by the year 2030, the price of new FCETs may range from 140,000 € to 250,000 € (adjusted for exchange rates) [34,108–115], which is on average lower than current retrofitting costs with hypothetical 80 % subsidies. However, the present study focuses on retrofitted vehicles for two reasons. First, there is a lack of new FCET models from large OEMs available on the market, which also inhibits the comparison of purchase prices. Second, there is a rationale to extend the operation of vehicles that may have been used as ICETs and can be transformed into ZEVs instead of being disposed of. Furthermore, the process of retrofitting ICETs with FCETs would lead to an increased demand for fuel cell vehicle components and hydrogen. This, in turn, could facilitate further cost reductions in the near future.

In addition, the impact of subsidies on the TCA shows that they currently promote a late retrofitting. Cutting subsidies has led to a higher TCA and has increased spreads especially for higher carbon hydrogen production pathways and late retrofitting periods. This finding reveals a disincentive, since from a rational point of view the retrofitted vehicle should not be sold after one or two periods of ownership. In contrast, lowering subsidies is also linked to shifting the retrofitting optimum to earlier retrofitting periods, although the costs of CO_2 abatement generally rise. A low hydrogen price, utilizing hydrogen from RES with a medium to high subsidy level, should be pursued to avoid this disincentive and to achieve effective cost reductions per saved unit of CO_2.

Furthermore, a sufficiently extended hydrogen infrastructure is necessary for a successful market adoption of FCETs. Recently, the European Parliament and Council have passed the Regulation for the deployment of alternative fuels infrastructure (AFIR), which includes among others a mandatory number of hydrogen fuel stations from 2030. The target requires that every 200 km and in all urban nodes there has to be a hydrogen fuel station along the TEN-T core network [116].

We have also shown that the increase in toll costs may have a substantial effect on TCO, especially in late retrofitting periods and low

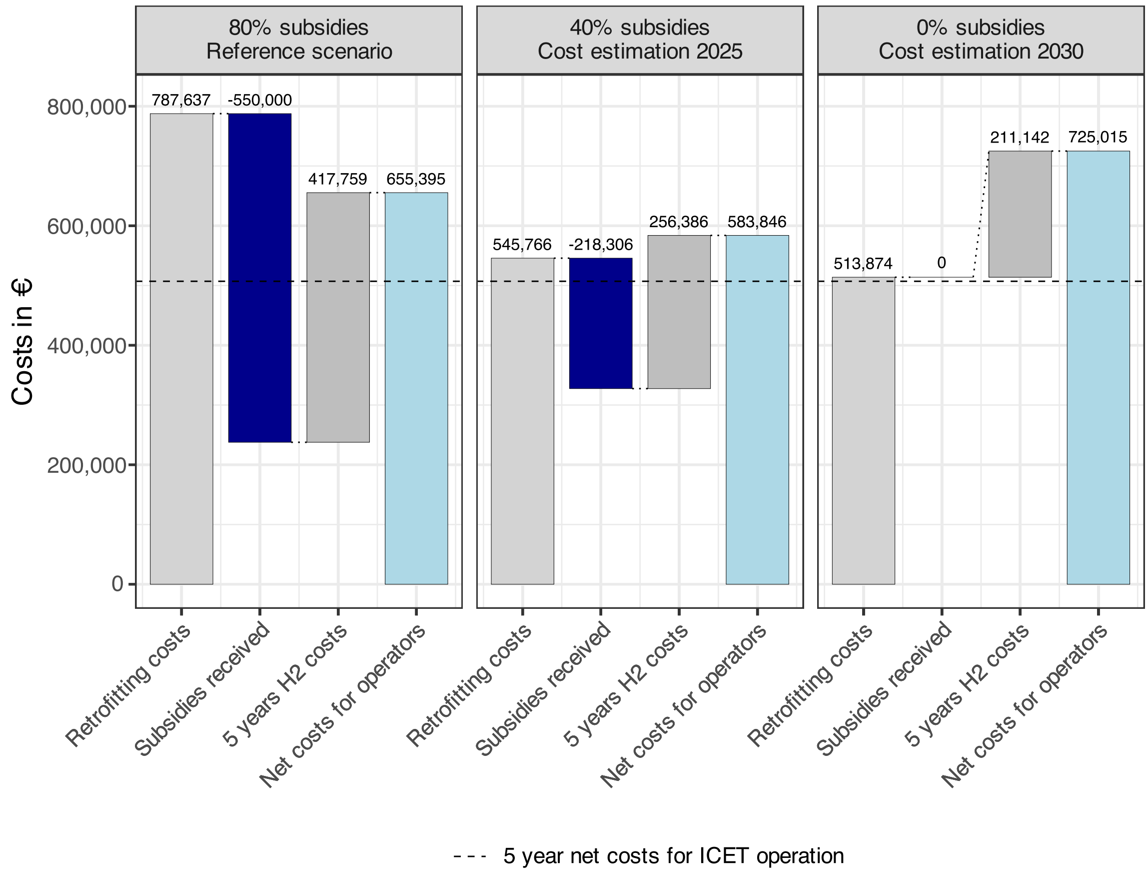

Fig. 14. Impact of subsidy reduction and future technological development for 40t trucks.

hydrogen scenarios. A CO_2 toll cost of 200 $\frac{€}{t_{CO_2}}$ is graduated by the GVWR and until 2026 ZEVs are exempted from conventional toll costs (see Table 7) [4,106]. This might lead to incentivization towards an early purchase or retrofitting of FCETs. However, our findings show that this is not an accurate representation of actual emissions from retrofitted vehicles because all retrofitted FCETs with SMR pathways emit more than their diesel counterparts. Disincentives could therefore result from exempting all ZEVs from toll costs. A more comprehensive WTW approach could prevent these disincentives. This also applies to the regulation of CO_2 emissions standards for HDV fleets by the European Commission [116,117]. One of the largest European operators of hydrogen refueling stations, H2Mobility, therefore recently implemented a model that offers green hydrogen at a reduced price compared to the conventional pathway.

Meanwhile the GHG quota set by both the German government [118] and the EU's Renewable Energy Directive III [119] attempts to address this issue by incorporating upstream emissions, GHG emissions from fuels, and promoting the production of hydrogen generated from renewable energy sources. Yet, the aforementioned policy instruments consist of directives and regulations that have nationwide and European efficacy. This indicates that a holistic approach, taking into account WTW emissions more comprehensively, would promote the attainment of rendering HDV transport more economically viable and environmentally sustainable.

From a customer perspective, our findings indicate that freight forwarders should factor in how long the ownership of a vehicle should last and at what timing a retrofitting would be likely to minimize costs effectively. Moreover, they should take into account that retrofitting existing fleets after their intended use time (6 to 7 years) might be a good solution to achieve an overall low TCO, even if hydrogen prices tend to be high. However, given that retrofitting costs and fuel costs are the primary contributors in most cases, and especially in high-share RES pathways, freight forwarders should prioritize these cost categories.

Therefore, our results suggest that hydrogen prices should be at least under 5 $\frac{€}{kg\ H_2}$ or lower and GHG emissions should be close to zero to effectively reduce emissions economically and to make retrofitting worthwhile for owners, with the present retrofitting costs and subsidies used in this study. In that case, it is to a lesser extent a matter of retrofitting timing. Although our results show that in most cases the penultimate year of ownership is the most rational period for retrofitting from a cost perspective, practical implementation is at odds with this finding because HDVs will likely be used for several more years after the retrofitting. Especially the borderline cases are less realistic, as a heavy-duty truck is typically not operated for ten, nine, or eight years by one user in one drivetrain topology. But for the general analysis of the impact of the retrofitting timing on the TCO, this consideration illustrates general behavior well. The more realistic scenarios are those in a range of three to six years per drivetrain topology. This is also the case for the TCA, where we found that the optimal time for retrofitting was either in the first few years or halfway through the vehicle's lifetime.

5. Conclusions

In this article, we have investigated how retrofitting ICETs into FCETs impacts their economic and environmental performance, while identifying the time-based effect of retrofitting and examining the trade-offs between the economic and the environmental performance. For that purpose, we developed a model to calculate the TCO by incorporating retrofitting costs among others. Furthermore, we evaluated the GWP to finally determine the TCA.

Our research suggests that retrofitting could become a key significant factor in reducing GHG emissions in road transportation, as the rollout of FCETs by OEMs may take time. At present, however, retrofitting is not a feasible option, because the economic viability depends on several factors. We found that especially the hydrogen production pathway has a major impact on economic and CO_2 abatement results. Here, we can observe for all pathways that later retrofitting periods are economically more attractive, while the abatement cost potential supports earlier to medium-period retrofitting by tendency.

For policymakers, we recommend that subsidies be reconsidered and that hydrogen infrastructure be greatly extended in order to reach reasonable price levels of hydrogen. Although we found that SMR could be a way to reduce TCO in the short term, the hydrogen production should however only be extended with RES, since it strongly affects the TCA.

For fleet operators, switching to FCETs by retrofitting their fleets is not favorable currently as subsidies have been cut in Germany. While only the LCECEL pathway showed lower costs or cost parity when subsidies were at the level of 80 %, other renewable pathways, such as H2M or GEDEL, only showed cost parity with ICETs at later retrofitting periods with higher-cost pathways. The related key findings can be summarized as follows:

- Hydrogen prices must be at least under 5 $\frac{€}{kgH_2}$ to ensure economic competitiveness of FCETs with ICETs when subsidies are taken into account. Otherwise, no pathway can be regarded to be a feasible option in comparison to the operation of a conventional powertrain.
- Longer lifetimes of HDVs facilitate important cost reductions for retrofitting.
- RES with low-carbon emissions are a prerequisite for effectively yielding good results for the TCA.
- Subsidies are crucial for decreasing the TCO and TCA of FCETs. Therefore, it is necessary to resume the provision of subsidies until CAPEX and component costs of FCETs decrease substantially.
- Toll costs noticeably raise the TCO of ICETs.
- An increase in annual mileage, retrofitting costs, and diesel fuel costs impact GVWRs similarly, while purchase costs play a minor role for higher GVWRs.
- The reduction of retrofitting costs for HDVs needs to be the target of further development efforts. Especially the costs for the fuel cell system as well as for the hydrogen storage system need to be decreased.

This study is limited by the lack of currently available data on the vehicle cycle of FCETs, which would expand the results by incorporating the environmental impact of several vehicle ages at retrofitting and including the end-of-life conditions of vehicle components. It could be of interest to further investigate to what extent the reuse or recycling of disassembled vehicle components affects the economic and environmental timing of retrofitting. Moreover, our analysis is restricted to Germany. Future research could therefore tie in with including other countries in Europe to determine how policies, local directives, and prices affect the attractiveness of retrofitting.

CRediT authorship contribution statement

Julius Hausmann: Visualization, Software, Investigation, Data curation, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Achim Kampker:** Writing – review & editing, Supervision, Conceptualization, Validation, Methodology. **Tim Kemperdick:** Visualization, Software, Investigation, Data curation, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Peter Letmathe:** Writing – review & editing, Supervision, Conceptualization, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Appendix A.1. Supplements to the TCO model

In this section, additional information and data on the development of the TCO model are provided.

Appendix A.1.1. Exchange and inflation rates

The exchange rate and the inflation rate used in this study are provided in Table Appendix A.1 and Appendix A.2.

Table Appendix A.1
Exchange rates EUR to USD.

Year	US-Dollar - Euro exchange rate [$\frac{US\$}{€}$]	Source
2015	1.11	[120]
2016	1.11	[120]
2017	1.13	[120]
2018	1.18	[120]
2019	1.12	[120]
2020	1.14	[120]
2021	1.18	[120]
2022	1.06	[120]

Table Appendix A.2
Inflation rates.

Year	Inflation rate [%]	Source
2019	1.20	[121]
2020	0.30	[121]
2021	2.30	[121]
2022	8.30	[121]
2023	5.80	[121]
2024	2.40	[121]
2025	2.40	[121]

Appendix A.1.2. Scrap value determination

The Tables Appendix A.3 and Appendix Appendix A.4 allow the determination of the scrap value of heavy duty-vehicles.

Table Appendix A.3
Scrap value of heavy-duty vehicle glider.

Material	Mass $[kg]$	Material Price $[\frac{€_{2022}}{kg}]$	Value per vehicle $[€_{2022}]$	Description	Source
Steel	3204.80	0.63	2020.81	WA72044910	[73]; [74]
Iron	400.00	0.63	252.22	WA72044910	[73]; [74]
Rubber	280.70	1.03	289.69	WA40040000	[73]; [74]
Aluminum	152.30	2.18	332.78	WA76020090	[73]; [74]
Copper	119.30	7.71	919.95	WA74040010	[73]; [74]
Magnesium	1.00	4.55	4.55	WA81042000	[73]; [74]
Zinc	0.40	2.28	0.91	WA79020000	[73]; [74]
Total per glider			3820.91		

Table Appendix A.4
Scrap value of a heavy-duty vehicle fuel cell system (40-ton vehicle).

Material	Mass $[kg]$	Material Price $[\frac{€_{2022}}{kg}]$	Value per vehicle $[€_{2022}]$	Description	Source
Stainless Steel	156.50	1.62	253.76	WA72042190	[51]; [74]
Steel	93.50	0.63	58.96	WA72044910	[51]; [74]
Wrought Aluminum	84.00	2.18	183.54	WA76020090	[51]; [74]
Rubber	32.50	1.03	33.54	WA40040000	[51]; [74]
Copper	8.50	7.71	65.55	WA74040010	[51]; [74]
Cast Iron	0.40	0.49	0.20	WA72041000	[51]; [74]
Platinum	0.10	29309.88	2930.99	London Metal Exchange	[51]; [122]
Nickel	0.01	18.00	0.18	WA75030010	[51]; [74]
Total per FCET			3526.71		

Table Appendix A.5
Scrap value of heavy-duty vehicle HV battery system (40-ton vehicle).

Material	Mass $[kg]$	Material Price $[\frac{€_{2022}}{kg}]$	Value per vehicle $[€_{2022}]$	Description	Source
Copper	122.77	7.71	946.68	WA74040010	[51]; [74]
Wrought Aluminium	212.05	2.18	463.33	WA76020090	[51]; [74]
Steel	15.62	0.63	9.85	WA72044910	[51]; [74]
Electronic Parts	12.28	7.34	90.08	WA85493900	[51]; [74]
Total per FCET			1509.94		

Table Appendix A.6
Scrap value of a heavy-duty vehicle internal combustion engine.

Material	Mass $[kg]$	Material Price $[\frac{€_{2022}}{kg}]$	Value per vehicle $[€_{2022}]$	Description	Source
Steel	342.00	0.63	215.65	WA72044910	[51]; [74]
Iron	513.00	0.63	323.48	WA72044910	[51]; [74]
Rubber	51.30	1.03	52.94	WA40040000	[51]; [74]
Wrought Aluminum	171.00	2.18	373.63	WA76020090	[51]; [74]
Plastic	51.30	3.89	199.59	WA39159080	[51]; [74]
Copper	11.40	7.71	87.91	WA74040010	[51]; [74]
Total per ICET			1253.20		

Appendix A.1.3. Levelized cost of hydrogen calculation inputs

Table Appendix A.7
Levelized cost of hydrogen CAPEX inputs.

CAPEX	Cost	Value	Unit	Source
AEL	Installed electrolyzer power	1	MW	Assumption
	Purchase cost	800	$\frac{€}{kW}$	Median value of [13,123,124]
Electric compressor	Purchase cost	$4,785 \cdot P_E^{0.66}$	€	[13,125]
Energy management unit	Purchase cost	10	Percentage of Sum of AEL System and EC System	[83]
Buffer storage vessel purchase cost	Purchase cost	$300 \cdot m_{H2} \cdot T$	€	[13,126]
Dispensing system purchase cost	Purchase cost	67.595	Euro per Unit	[13]
Additional system costs	Installation	20	Percentage of purchase costs	[13]
	Engineering	15	Percentage of purchase costs	[13]
	Others	50	Percentage of purchase costs	[13]

Table Appendix A.8
Levelized cost of hydrogen CAPEX inputs.

Component	Cost	Value	Unit	Source
AEL	Capacity factor	0.95	%	[124]
	Operating hours per year	8400	$\frac{h}{year}$	Median value of [13,123,124]
	Specific energy consumption	48	$\frac{kWh}{kg\ H_2}$	[13,124]
	Grid electricity costs	0.2837	$\frac{€}{kWh}$	[127]
	Water consumption	22.22	$\frac{l_{H2O}}{kg\ H_2}$	[123]
	Water price	2.7	$\frac{€}{m^3}$	Average value of [123,124]
	OM	0.03	% of AEL System CAPEX	Average value of [123,124]
Electric compressor	Specific energy consumption	3.4	$\frac{kWh}{kg\ H_2}$	[13]
	OM	0.02	% of CAPEX	[13]
Energy Management Unit	Efficiency energy management unit	0.9	η_{EMU}	[13]
Buffer storage vessel	Operating costs	0.02	% of total CAPEX	[13]
Dispensing system	Operating costs	0.02	% of total CAPEX	[13]

Appendix A.1.4. Integration markup

Two literature sources provide data for the integration markup.

Table Appendix A.9
Integration markup for the heavy-duty vehicle retrofitting from the literature.

Value	Source	Scenario
1.364	[81]	Low
1.436	[81]	Average
1.56	[81]	High
1.36	[80]	–

Appendix A.1.5. Fuel consumption of conventional heavy-duty vehicles

Table Appendix A.10
Fuel consumption of conventional heavy-duty vehicles in [$\frac{L}{100\ km}$].

18 ton	26 ton	40 ton	Source
27.1	28.8	32	[66]
n.a.	n.a.	33	[128]
n.a.	n.a.	27	[109]
n.a.	n.a.	40	[30,129]
n.a.	n.a.	30.7	[30]
n.a.	n.a.	29.86	[93]
n.a.	27	30	[130]
21.51	25.48	29.41	[29]
n.a.	n.a.	30.8	[92]
n.a.	n.a.	36.4	[131]
n.a.	n.a.	35	[132]
31.1	n.a.	32.6	[133]
n.a.	25.21	25.51	[13]
n.a.	n.a.	28	[30,134]
n.a.	n.a.	40	[30,110]
27.1	**26.26**	**30.8**	**Median**

Appendix A.2. Supplements to the LCA model

Table Appendix A.11
Inputs per kilogram of hydrogen for the steam methane reforming LCI in the WtT Fuel-Life Cycle.

	Process	Flow	Amount	Source
Input	Hydrogen Production	Natural Gas	1.990 $\frac{kg}{kg_{H2}}$	[101]
		Water	4.468 $\frac{kg}{kg_{H2}}$	[101]
		Electricity	0.556 $\frac{kWh}{kg_{H2}}$	[101]
		Heat	13.125 $\frac{kWh}{kg_{H2}}$	[101]
Output	Hydrogen Production	Carbon Dioxide	5.458 $\frac{kg}{kg_{H2}}$	[101]
Input	Compression before distribution	Electricity	3.027 $\frac{kWh}{kg_{H2}}$	[60]
Input	Distribution	Transport	1.900 $\frac{tkm}{kg_{H2}}$	[60]
Input	Compression before fueling	Electricity	3.139 $\frac{kWh}{kg_{H2}}$	[60]
Input	Fueling	Electricity	1.033 $\frac{kWh}{kg_{H2}}$	[60]
Output	**WtT**	Hydrogen in vehicle	**1** $\frac{kg}{kg_{H2}}$	

Table Appendix A.12
LCI of the steam methane reforming process.

	Process	Flow	Amount
Input	Fuel Cell	Hydrogen in vehicle	1 $\frac{kg}{kg_{H2}}$
		Nitrogen (from air)	25.826 $\frac{kg}{kg_{H2}}$
		Oxygen (from air)	7.936 $\frac{kg}{kg_{H2}}$
Output	Fuel Cell	Released energy	33.331 $\frac{kWh}{kg_{H2}}$
		Nitrogen	25.826 $\frac{kg}{kg_{H2}}$
		Water	8.936 $\frac{kg}{kg_{H2}}$

Table Appendix A.13
LCI of the alkaline electrolysis process.

	Process	Flow	Amount	Source
Input	Electrolyzer	Electricity	53.33 $\frac{kWh}{kg_{H2}}$	[13]
		Water	22.22 $\frac{kg}{kg_{H2}}$	[13]
Output	Electrolyzer	Oxygen	7.936 $\frac{kg}{kg_{H2}}$	Assumption
		Water	13.284 $\frac{kg}{kg_{H2}}$	Assumption
Input	Electric Compressor	Electricity	3.780 $\frac{kWh}{kg_{H2}}$	[13]
Output	**WtT**	Hydrogen in vehicle	**1** $\frac{kg}{kg_{H2}}$	

Table Appendix A.14
Processes from ecoinvent 3.8.

Flow	Process in ecoinvent
Natural Gas	market for natural gas, low pressure | natural gas, low pressure | Cutoff, S (RoW)
Water	water production, deionised | water, deionised | Cutoff, U (Europe without Switzerland)
Electricity Grid	electricity, high voltage, production mix | electricity, high voltage | Cutoff, S (Germany)
Electricity Renewable	electricity production, wind, >3 MW turbine, onshore | electricity, high voltage | Cutoff, S (Germany)
Transport	market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, U (Europe)

Data availability

Data will be made available upon request.

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