Funded by
the European Union

Project Title:

Eco-operated, Modular, highly efficient, and flexible multi-POWERtrain for long-haul heavy-duty vehicles

Acronym: **EMPOWER**

Grant Agreement No.: **101096028**

Topic:	**Modular multi-powertrain zero-emission systems for HDV (BEV and FCEV) for efficient and economic operation (2ZERO)**
Topic identifier:	**HORIZON-CL5-2022-D5-01-08**
Type of action:	**Innovation Action (IA)**

Deliverable No.	D1.3	
Deliverable Title	LCA and TCO assessment of baseline vehicles	
Deliverable Date	2024-06	
Deliverable Type	Report	
Dissemination level	Public	
Written by	Ezio SPESSA (POLITO) Antonella ACCARDO (POLITO) Trentalessandro COSTANTINO (POLITO) Gaia GENTILUCCI (POLITO) Xavier GUICHET (IFPEN)	2024-05-15 2024-05-15 2024-05-15 2024-05-15 2024-05-15
Checked by	Claudio MEZZA (IVECO) Ettore GUALANDI (GLO)	2024-06-18 2024-06-25
Approved by	WP Leader Dragan SIMIC Thomas BÄUML	 2024-06-27 2024-06-28
Status	Version 1.0 Version 1.1	2024-05-15 2024-06-28

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Publishable Executive Summary

The European Union (EU) seeks to decouple economic growth from resource use and achieve carbon neutrality across all sectors by 2050.

From the environmental point of view, global CO_2 emissions and increasing temperatures require a major decarbonization effort to reach carbon neutrality by 2050. To accomplish this goal, the transport sector needs a major switch towards vehicles with zero tailpipe emissions. The majority of Heavy-Duty Vehicles (HDVs) and buses is still diesel-based. Zero-Emission Heavy-Duty Vehicles (ZE HDVs) with comparable performance to diesel-based HDVs are paramount to meet the carbon neutrality goal. Eliminating tailpipe emissions will reduce pollutant emissions, clean the air, reduce noise, improve accessibility, and enhance urban and peri-urban environments. In addition, while environmental, and energy-related vehicle regulations have primarily focused on tailpipe energy use and emissions in the past, these do not account for the full environmental impacts of vehicle use. Recent efforts aim to harmonise international regulations on tailpipe emissions and expand their scope to include emissions from other life-cycle phases. These include vehicle production, especially in the case of vehicles using batteries, and emissions from hydrogen production and electricity generation. The Life Cycle Assessment (LCA) approach is used worldwide as a valid approach to evaluate the environmental impacts of products along their entire life cycle.

From the economic point of view, nowadays, the cutting-edge effort for the deployment of ZE HDVs is enhancing performance while lowering production and operational costs to compete with conventional technologies. The affordability and reduction of operational costs of ZE HDVs will improve user adoption, allowing the technology to scale up its carbon reduction potential.

Furthermore, it is worth noticing that in the EU market, in 2020, only 0.24 % were zero-emission vehicles, providing a huge potential for the transformation of the transport sector to ZE HDVs by 2050. With the massive shift towards ZE HDVs, the aim is to generate major benefits for citizens’ health and quality of life, but also support EU economic growth, creating a solid base for new business opportunities. The financial resources allocated by the EU to achieve these goals are significant, totalling 600 million € from the Next Generation EU Recovery Plan and a major portion of the EU multi-annual financial framework programme 2021-27, which includes Horizon Europe. This places the EU at the forefront of the new Green Economy.

Hence, both the environmental and economic perspectives should be considered when ZE HDVs need to be compared with conventional counterparts.

The objective of EMPOWER is to deliver two modular and flexible ZE HDVs. One of the demonstrators will be a Fuel Cell Electric Vehicle (FCEV) suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km. The second one, a Battery Electric Vehicle (BEV), will be designed for regional distribution mission profiles with a maximum uncharged driving range of 400 km. Based on the above facts, and according to the objectives and ambition, EMPOWER has the strategic vision of (1) delivering the next generation of affordable and highly efficient ZE HDVs, (2) accelerating the uptake of zero tailpipe emission, user-centric solutions for road-based mobility, and (3) supporting the European economic growth and providing a solid base for new business opportunities.

This deliverable focuses on the activities of WP1 (Task 1.4). The aim of this task is twofold.

First, it aims to evaluate a reliable 2020 diesel baseline truck in terms of environmental LCA and Total Cost of Ownership (TCO), covering all life cycle phases (e.g., production, use phase, end of life, with all influencing parameters included in the analysis: materials, resources, processes, etc.). This baseline is intended to be used as a reference point for comparison with the two EMPOWER demonstrators that will be developed during the project. In fact, during WP7 (Task 7.4), the LCA and TCO of the two demonstrators will be evaluated and compared with the selected baseline.

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Second, the aim of Task 1.4 is to preliminarily assess the LCA and TCO of the EMPOWER demonstrators. The preliminary assessments aim to evaluate decarbonization potentials of the demonstrators against their conventional counterparts as well as forward-looking TCO reductions assuming mass production. Employing comparative LCA and TCO analysis among the baseline vehicles and the demonstrators, this task aims to identify their environmental and financial ramifications, providing inputs for conscious decision-making.

Polytechnic of Turin (POLITO) and IFP Energies nouvelles (IFPEN) conducted the activities related to WP1 (Task 1.4) taking the final aim within the EMPOWER project in mind, which is to perform 1) a detailed LCA study of the developed demonstrators to identify the minimum achievable impact on environment, representative values for CO_2 emissions, and potential improvements in the environmental impact of the technological solutions on vehicle and system level; 2) an analysis of the TCO of the two demonstrators to reveal the economic impact. By comparing the TCO and LCA results of different vehicles, a clearer understanding of the financial and environmental implications of each vehicle over its lifetime can be gained, thereby informing more sustainable and economically sound decisions. TCO and LCA assessments serve as vital tool for decision-makers, enabling the choice on the most economically and environmentally sustainable path.

First, an exhaustive literature review has been conducted to identify the state-of-the-art 2020 diesel baseline truck (see paragraph 2.2 for LCA literature review and paragraph 3.2 for TCO literature review). Regrettably, this attempt underscored a glaring deficiency in reliable data availability. During WP1 Task 1.4, two decisions have been taken which have resulted in addition to the original proposal: (1) two baselines (and not one) have been identified as representative of the 2020 diesel baseline trucks in EU; (2) the baselines have been evaluated employing Iveco Group (IVG) company-specific data. In fact, despite the two demonstrators being both HDVs of the same Vehicle Energy Consumption Calculation Tool (VECTO) group, they are intended to be used in different operation conditions and necessitate two comparable diesel counterparts. Furthermore, the use of company-specific data is always beneficial for LCA and TCO assessments, hence this decision will not harm the project final aim. LCA and TCO analysis based on company-specific data rather than literature data benefit of more solid data and high-reliability in the achieved results. Moreover, using company-specific data, the LCA models that are going to be developed in WP7 will benefit from the work conducted in WP1. In fact, the two demonstrators will be designed and prototyped so that several components will be taken as carryover from the diesel configurations while other systems will be removed or added to the diesel configurations based on their functions. Instead, the results of the literature review serve to depict how POLITO's and IFPEN's assumptions are localized in the existing literature and to validate the results obtained in this deliverable.

Second, for the LCA and TCO models of the two 2020 diesel baseline trucks, major details have been reported in paragraph 6 and 7. Results are respectively reported in paragraphs 8.1.1 and 8.2.1.

Lastly, a preliminary cradle-to-grave LCA study of the two demonstrators (paragraphs 6.7 and 6.8), covering all life cycle phases has been performed to preliminary estimate their positive effect on environmental impact and circularity. Then, the LCAs of the two demonstrators have been compared with the LCAs of the two baselines. For the FCEV demonstrator (paragraphs 6.7), four scenarios have been set up based on diverse hydrogen production routes: steam methane reforming (SMR), steam methane reforming with carbon capture and storage (SMR + CCS), Alkaline Electrolysis (AE) using fossil-based electricity from the EU mix, and green hydrogen produced via AE using offshore wind-based electricity. Therefore, four scenarios have been set up, namely “FCEV-SMR”, “FCEV-SMR+CCS”, “FCEV-AE fossil based” and “FCEV-AE wind based”.

The LCA model of the hydrogen tank as well as the LCA model of the FC system (paragraph 6.7.2) have been performed based on secondary data but fine-tuned to suit the EMPOWER demonstrator requirements. For the BEV demonstrator (paragraph 6.8), similar to the FCEV demonstrator, two electricity mixes have been compared, namely fossil-based from the EU mix and offshore wind-based. Therefore, two scenarios

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

have been set up, namely “BEV” and “BEV wind”. The LCA model of the Li-ion battery pack (paragraph 6.8.1) has been performed. A preliminary TCO evaluation of the two demonstrators has been conducted (paragraph 8.2.2). Then, the TCOs of the two demonstrators have been compared with the TCOs of the two baselines. The preliminary evaluation includes an initial projection scenario that accounts for the reduction in component prices due to mass production by 2030 and 2050. For the FCEV demonstrator, four scenarios related to hydrogen production and costs have been investigated: SMR, SMR+CCS, electrolysis using electricity from the EU grid, and green hydrogen produced via electrolysis powered by renewable energy sources.

For both LCA and TCO, it has been assumed that the FCEV demonstrator is equipped with two battery packs while the BEV demonstrator with 7 batteries.

Key findings are summarized hereafter. For both the baselines and almost all the scenarios investigated for the EMPOWER demonstrators, the main driver to the GWP has been found to be the Well-To-Tank (WTT) phase. Conversely, for the BEV demonstrator scenario with wind-based electricity, the raw material acquisition phase has been found to be the main driver accounting for 57 % of the overall GWP impact. This outcome demonstrates that the more the decarbonization strategy is effective and the GWP reduced, the more the impact shifts towards vehicle production and raw material supply. Lastly, compared to the DIE-LH, the scenario in which hydrogen is produced by means of AE with wind-based electricity resulted to be the least impactful allowing for a GWP reduction of 80 %. Compared to the DIE-R, the BEV scenario with wind-based electricity resulted as the least impactful allowing for a GWP reduction of 89 %.

The comprehensive LCA results (assessing not only GWP but also other impact categories) have shown that the WTT phase emerged as the most impacting phase in almost all impact categories. Conversely, the acquisition of raw materials emerged as the most impacting phase in the mineral and metal resource use category. This highlights the need for efficient circular economy strategies coupled with decarbonization strategies. In this study, the vehicle and the Li-ion battery packs have assumed to be recycled and credits are given as a benefit for the avoided production of virgin materials.

Moving from the vehicle level to the part level, ad-hoc LCA models have been developed for the Li-ion batteries, FC system, and hydrogen tanks. It is worth noting that, for the FCEV demonstrator, the catalyst has been found to be the most environmentally impactful component in the FC system, primarily attributed to the presence of platinum. This is attributable to the significant energy consumption and Greenhouse Gas (GHG) emissions associated with platinum production, encompassing mining, processing, and refining stages. For the BEV demonstrator, the GWP of the Li-ion battery has been found to be predominantly influenced by raw material extraction and manufacturing phases. This is mainly due to battery cell production, with cobalt sulphate and nickel sulphate being the primary contributors, alongside electricity consumption and lithium carbonate. The EoL phase, particularly the recycling process, marginally affected the GWP. However, notable environmental burdens are observed in ozone depletion, ionizing radiation, photochemical ozone formation, terrestrial eutrophication, land use, and fossil resource consumption during the recycling process. This is chiefly attributed to diesel utilization as fuel in the recycling process, thereby indirectly impacting diesel production.

For the TCO, the two baselines were evaluated across their entire life cycles, from purchase to EoL, which represents the resale phase for fleet operators. Key determinants influencing the economic viability of the demonstrators, notably purchase cost and energy carrier cost, were identified, collectively constituting over 50% of the overall economic evaluation. While certain costs, such as driver expenses, remained constant and beyond immediate control, the focus remained on controllable aspects, particularly the subsystems of the demonstrators. Through targeted efforts aimed at mass production and consequent cost reductions in components like battery packs, fuel cell stacks, and hydrogen tanks, efforts aim to achieve TCO parity in 2030 and a TCO reduction over the 2030s. Furthermore, the critical importance of the energy carrier, lying beyond direct manufacturer control, was emphasized. Thus, a comprehensive exploration of various scenarios is essential to equip policymakers with the insights necessary for guiding the freight transport sector towards decarbonization, aligning with the overarching goals of the EMPOWER project.

Further improvements and scenarios are under study for development during WP7 and deployment in deliverable D7.1. The aim is to better depict the future 2029 situation when the demonstrators are expected to approach the market. Among the main aspects, great efforts are in place from both POLITO and IVG to increase the primary data coverage in the LCA and TCO results of both the baselines and the EMPOWER demonstrators. All the models developed during the preliminary LCA and TCO assessment will be fine-tuned during the project according to the future advancements in the demonstrator design.

Table of Contents

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

List of Tables

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Abbreviations and Nomenclature

Table 1: List of Abbreviations and Nomenclature

Symbol or Shortname	Description
ZE HDV	Zero-Emission Heavy-Duty Vehicles
LCA	Life Cycle Assessment
TCO	Total Cost of Ownership
GHG	Greenhouse Gas
FC	Fuel Cell
VECTO	Vehicle Energy Consumption Calculation Tool
DIE-R	2020 diesel baseline truck with regional distribution mission profile
DIE-LH	2020 diesel baseline truck with long-haul distribution mission profile
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
EoL	End of Life
SMR	Steam Methane Reforming
CCS	Carbon Capture and Storage
GWP	Global Warming Potential
AE	Alkaline Electrolysis
HDV	Heavy-Duty Vehicles
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment method

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

1. Introduction

The escalating worldwide CO_2 emissions and rising temperatures underscore the urgent necessity for a significant decarbonization in our economies and ways of living. In December 2019, the EU approved the European Green Deal Action Plan [1] intending to transform the Union into a modern, resource-efficient, competitive, and inclusive economy. The plan aims to decouple economic growth from resource use and achieve full carbon neutrality in all economic sectors by 2050. In 2020, the transport sector in the EU-27 was responsible for almost 27% of CO_2 emissions [2].Approximately 5.6% of emissions are generated by HDVs and buses [3]. Moreover, a study conducted by the European Automobile Manufacturers' Association (ACEA) found out, that in 2020 about 6.2 million medium and heavy-duty commercial vehicles were on the EU's roads [4]. Hence, this sector requires a significant transition to zero tailpipe emissions to accomplish complete carbon neutrality by 2050. Transitioning to zero tailpipe emission road mobility will result in concrete advantages such as decreased pollutant emissions, cleaner air (including unregulated pollutants, nanoparticles, and secondary pollutants), reduced noise, improved accessibility, and enhanced urban and peri-urban environments.

To reach the prospected goals, ZE HDVs with a similar performance as conventional HDVs are necessary. Nowadays, the challenge is not demonstrating technologies for electrification, but instead improving their performance while cutting their production and operational costs, with the aim of reaching competitiveness against their conventional counterparts. The resulting affordability of ZE HDVs together with the expected reduction of operational costs will increase their user acceptance, allowing the technology to deploy its carbon reduction potential at scale.

The objective of EMPOWER is to deliver two modular and flexible ZE HDVs of VECTO group 9, as define in [5], with a Gross Vehicle Weight (GVW) of at least 40 tons, both at Technology Readiness Level (TRL) 8. One of the demonstrators will be a FCEV suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km. The second one, being a BEV, will be designed for regional distribution mission profiles with a maximum unrecharged driving range of 400 km.

Within the EMPOWER project, a fundamental objective of WP1 (Task 1.4) is to develop the LCA model of a 2020 diesel baseline truck and estimate the current TCO achieved with the EMPOWER vehicle demonstrators (for the LCA, a brief introduction to the topic can be found in paragraph 2.1 while for the TCO, a brief introduction to the topic can be found in paragraph 3.1). The baseline is intended to be used as a reference point for comparison with the two EMPOWER demonstrators that will be developed during the project. The analysis of the two demonstrators will be performed during WP7 (Task 7.4) with data from the actual EMPOWER developments. Furthermore, besides the assessment of the two baselines, a preliminary estimation of the LCA and TCO of the two demonstrators have been performed. For the TCO the analysis has been conducted assuming a production volume of more than 10,000 trucks per year, trying to anticipate and estimate the cost reduction due to mass production.

For the selection of the baseline, the aim is to ensure that it is representative of the state-of-the-art in 2020, thereby accurately mirroring the current EU market and specific applications under consideration within the EMPOWER framework. According to [4], in 2020, approximately 96.3 % of EU trucks ran on diesel fuel, therefore a diesel powertrain has been chosen. Moreover, two baselines (and not one) have been identified to perform a fairer and more rigorous comparison with the two demonstrators, which are both HDVs of the same VECTO group but used in different operation conditions, i.e., long-haul, and regional distribution mission profiles. In fact, the main contributor to the impact of a diesel-based vehicle is the use phase, which is significantly different between long-haul and regional distribution mission profiles.

During WP1, first, a literature review has been conducted focused on the LCA (paragraph 2.2) and TCO (paragraph 3.2) of diesel oil-fuelled VECTO group 9 trucks. For the LCA, the aim is to find representative values of CO_2eq and identify the most important categories considered in an LCA study dealing with the LCA of HDVs. All the publications found have been scrutinized and investigated in terms of time coverage, geographical coverage, powertrain technology, replicability, functional unit, system boundary, annual mileage, vehicle lifetime, software, database, impact categories under the scope and Life Cycle Impact Assessment (LCIA) method, and carbon footprint (CO_2eq) results. The TCO literature review aims to establish a representative monetary value for two 2020 diesel trucks from the VECTO group 9 category. A systematic literature review has been conducted to explore the economic assessment of conventional heavy-duty vehicles. This literature review considers the primary parameters outlined in the environmental assessment (e.g., annual mileage, vehicle lifetime) but also cost types included in the model, inflation, and actualization of cash flows to ensure a comprehensive evaluation of the economic aspects of these vehicles. This approach aims to establish well-comparable baselines with the two demonstrators that will be developed within the project.

Regrettably, the literature review resulted in a glaring deficiency in reliable data availability, compelling a shift towards assessing the baselines employing IVG company-specific data. Therefore, the LCA and TCO of the baselines are not limited to the investigation of the literature studies, but two IVG-specific vehicle models have been identified as 2020 baseline diesel trucks. The reason for this choice is twofold: first, the results are solid and benefit of high-reliability, second the LCA models that are going to be developed in WP7 will benefit from the work conducted in WP1. The two demonstrators will be designed and prototyped so that several components will be taken as a carryover from the diesel configurations (e.g., front axles, suspensions, tag-axles, trailer connections) while other systems will be removed or added to the diesel configurations based on their functions (e.g., batteries, fuel cell system, hydrogen tanks). Instead, the results of the literature review serve to depict how POLITO’s assumptions are localized in the existing literature and to validate the results obtained in this deliverable. The use of company-specific data is always beneficial for LCA and TCO assessments, therefore this decision will not harm the project's final aim.

Second, the objective of WP1 is to develop the LCA and TCO model of a 2020 diesel baseline truck. Both the LCA and TCO models of the baseline trucks have been developed considering its full life cycle (e.g., production, use phase, end of life, with all influencing parameters included in the analysis: materials, resources, processes, etc.). Data to feed the models and the parameters influencing and needed for the LCA and TCO studies (materials, resources, processes, cost flows etc.) have been provided by all involved project partners along the value chain, while relevant databases, industrial reports, and literature studies have been used to fill data gaps. Major details on the LCA and TCO models developed during WP1 have been reported in paragraph 6 and 7. According to the previous paragraph, the LCA models, as well as the TCO models, of the two 2020 diesel baseline trucks have been developed from scratch based on IVG data.

Lastly, a preliminary cradle-to-grave LCA study (paragraphs 6.7, 6.8) and preliminary TCO study (paragraph 8.2.2) of the two demonstrators, covering all life cycle phases have been performed to preliminary estimate their positive effect on environmental impact, circularity, and economic impact. For the preliminary assessment of the FCEV demonstrator (paragraphs 6.7), four scenarios have been set up based on diverse hydrogen production routes. For the hydrogen tank, instead, 5 tanks with a total weight of 73 kg hydrogen have been included in the FCEV demonstrator in compliance with deliverable D1.1. A dedicated sub-task focused on performing the LCA of an FC system suitable for the EMPOWER long-haul heavy-duty truck (paragraph 6.7.2). For the preliminary assessment of the BEV demonstrator (paragraph 6.8), two electricity mixes, namely fossil-based and wind-based, have been compared. Therefore, two scenarios have been set up, namely “BEV” and “BEV wind”. The fossil-based electricity mix is the EU mix. In the regional distribution, it has been assumed that the BEV has been equipped with 7 batteries in compliance with deliverable D1.1. A dedicated subtask focuses on the LCA model of the Li-ion battery pack (paragraph 6.8.1).

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

For the preliminary TCO evaluation of the two demonstrators, the study aims to compare the demonstrators with two established baseline vehicles. The preliminary analysis includes an initial projection scenario that anticipates a reduction in component prices due to mass production by the years 2030 and 2050. Specifically for the FCEV demonstrator, four distinct scenarios concerning hydrogen production and associated costs were analyzed. These scenarios include hydrogen production through SMR (i.e., grey hydrogen), SMR+CCS (i.e., blue hydrogen), electrolysis using electricity from the EU grid, and green hydrogen production via electrolysis powered by renewable energy sources. This comprehensive approach ensures that the evaluation considers various future developments and technological advancements, providing a robust basis for comparing the economic viability of the demonstrators against conventional diesel trucks.

2. Introduction to Life Cycle Assessment and literature review

2.1 Introduction to Life Cycle Assessment

LCA is a structured, comprehensive, and internationally standardized method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services ("products"). LCA takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste [6] (Figure 1). LCA is often used as a relative tool, intended for comparison rather than absolute evaluation, and is used to help decision-makers choose between alternative courses of action [7]. The approach is increasingly being integrated with life cycle costing and social-LCA to encompass the three pillars of sustainability [7].

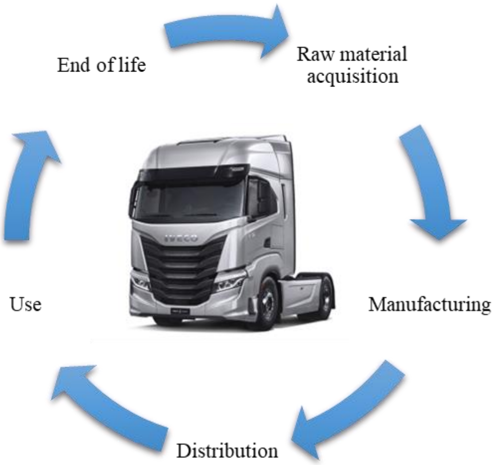


Figure 1: Life cycle of a product

ISO 14040 and 14044 are the main reference standards for practitioners of LCA and provide the indispensable framework for conducting an LCA study [6] . ISO 14044 details the requirements for conducting an LCA while ISO 14040 describes the principles and framework of an environmental assessment. According to the previous standards, the four phases of an LCA study are as follows:

1) Goal and scope definition;
2) Inventory analysis;
3) Impact assessment;
4) Interpretation and discussion of results.

The goal and scope definition phase refers to the determination of the object and purpose of the LCA study and the corresponding system boundaries. Second, the inventory analysis phase involves the collection of the data necessary to meet the goals of the defined study. It is an inventory of input/output data about the system being studied. The purpose of the impact assessment phase is to transform the long list of inventory data into a limited number of indicator scores by using a specific life cycle impact assessment method. These indicator scores express the relative severity of an environmental impact category, to better understand the environmental significance of the product, process, or service under study. In the phase of interpretation and discussion, the results of the impact assessment are summarized and discussed as a basis for conclusions, recommendations, and decision-making following the goal and scope definition [8].

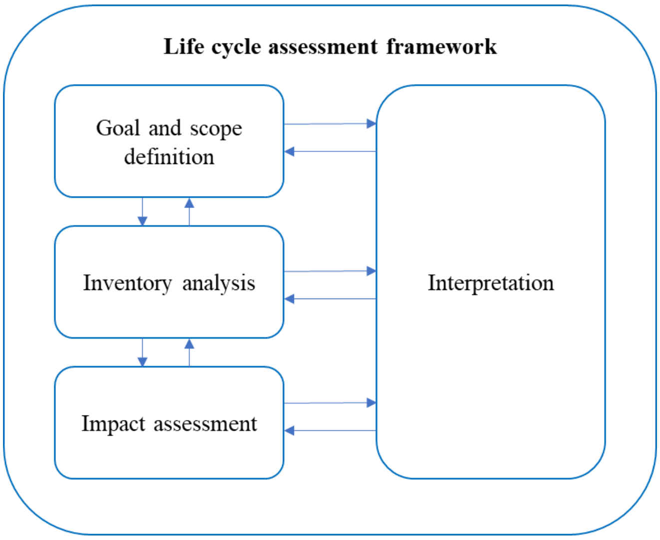


Figure 2: Phases of an LCA

In defining the scope and goal of an LCA, the main items that should be considered and clearly described are the product system to be studied, the functional unit, and the system boundary. The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure the comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis [9]. The system boundary determines which unit processes shall be included within the LCA. Decisions shall be made regarding which unit processes to include in the study and the level of detail to which these unit processes shall be studied. [10]. It is called cradle-to-grave boundary if the entire life cycle of a product is included in the study system (from raw material acquisition to disposal); while the cradle-to-gate assessment stops at the manufacturing phase and the end of life (EoL) is not considered.

Life cycle inventory (LCI) creation represents the second phase of an LCA study. It is also a crucial phase of an LCA study, involving the collection and compilation of data on elementary flows from all processes in a product system. This data is used for subsequent life cycle impact assessment [11]. Data may be directly measured or collected from production sites, suppliers, and distributors (primary data) or estimated (not directly collected, measured, and sourced from a third-party life-cycle-inventory database (secondary data). Using primary data is crucial because of its direct influence on the quality of the LCA study. Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system [9]. The LCI consists of data compilation to quantify resource use and emissions for each process in the defined system. Data for each unit process within the systems boundary can be classified under major headings, including:

- energy inputs, raw material inputs, ancillary inputs, other physical inputs,
- products, co-products and waste,
- emissions to air, discharges to water and soil, and
- other environmental aspects[9].

An LCI can draw upon multiple sources including primary data, academic literature, and LCI databases. The source used will depend on the specificity required for the assessment and data availability. The level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process [7]. The use

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

of primary data in LCA studies can enhance the specificity and representativeness of the results, particularly when considering the environmental performance of different systems. However, the exclusion of site-specific data from the inventory phase can introduce uncertainties and affect the reliability of the results [12]. Therefore, the LCI phase in LCA studies is a critical component that significantly impacts the final results [13]. To conduct a representative, specific and reliable LCA study, it is necessary to adopt as much primary data as possible.

The LCIA phase includes the collection of indicator results for the different impact categories, which together represent the LCIA profile for the product system. The LCIA consists of mandatory and optional elements. The LCIA phase shall include the following mandatory elements:

- selection of impact categories, category indicators and characterization models;
- assignment of LCI results to the selected impact categories (classification);
- calculation of category indicator results (characterization)[10].

The life cycle interpretation phase of an LCA study comprises:

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- an evaluation that considers completeness, sensitivity and consistency checks;
- conclusions, limitations, and recommendations [10].

2.2 LCA Literature Review

A systematic literature review has been conducted during WP1. Systematic literature reviews ensure that the starting point is grounded in the most recent and relevant research, setting the stage for meaningful comparisons and evaluations as the project progresses. Three main platforms have been considered for the search, namely Scopus, ScienceDirect, and Google Scholar. The search was carried out adopting the following fields:

- “Article title, abstract, keywords” in Scopus platform;
- “Title, abstract, keyword” in ScienceDirect and Google Scholar platforms.

“lca AND heavy AND duty AND vehicle” and “lca AND truck” were the keywords chosen for analyzing the evolution of LCA in the automotive field with a specific focus on HDVs. With the first search step, 482 papers were found. These are distributed across the platforms as follows: Scopus contributed 334 papers, ScienceDirect with 111, and Google Scholar with the remaining 37. A selection of papers was performed based on relevance and representative criteria. Duplicated papers were discharged. With this purpose, a time filter (2019-2023) was applied, and the resulting papers achieved were 24. In Figure 3, there is an overview of the LCA search procedure.

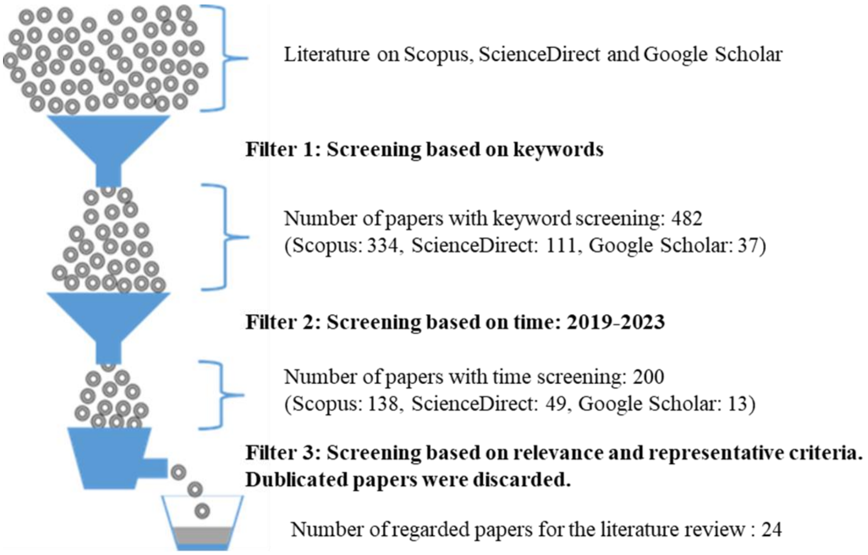


Figure 3: LCA Literature review workflow

The results of the literature review were compiled and schematized into graphs hereafter with the aim of making them more intuitive and understandable.

2.2.1 Time coverage

As described in the previous paragraph, a time filter has been applied during the search in order to have a representative LCA literature review for the 2020 baseline diesel truck. In Figure 4, there is an overview of LCA studies in the range 2019-2023. In 2020, the CO_2 emissions of the transport sector in the EU-27 accounted for approximately 27 %. Thereof about 5.6 % were produced by HDVs and buses [3]. Therefore, this sector calls for a massive shift to zero tailpipe emissions to achieve full carbon neutrality by 2050. Figure 4 shows an increase in LCA studies of trucks and heavy-duty vehicles, depicting the current need for further research on this topic. Analyzing the global trend, the growth of LCA studies has been significant over the years.

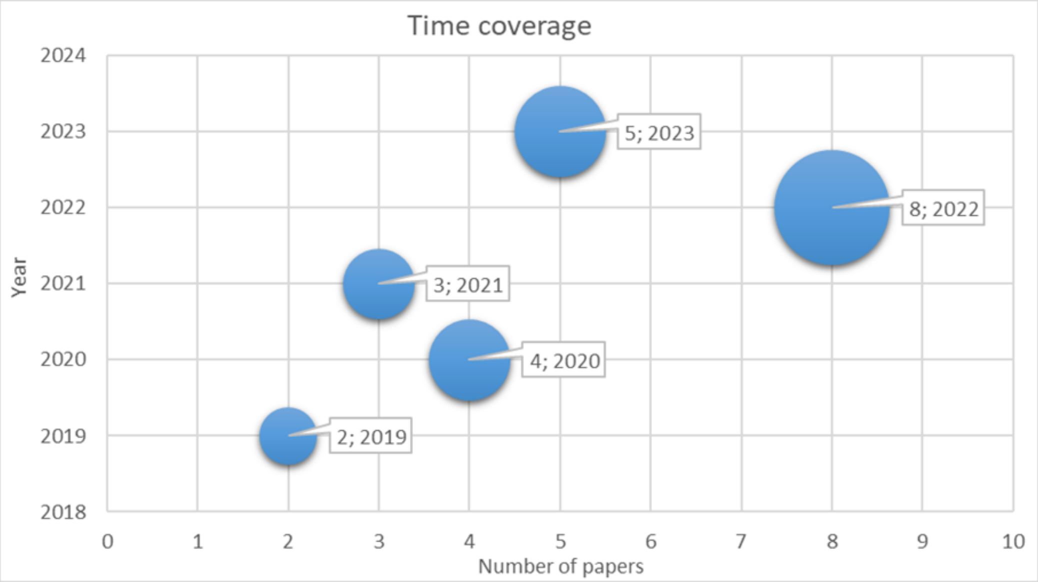


Figure 4: LCA Time coverage of LCA investigated studies

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

2.2.2 Geographical coverage

Geographical coverage is a key parameter in LCA studies. Figure 5 highlights the expansion of LCAs worldwide. The geographical dimension of LCAs, particularly in Europe, has seen significant growth and evolution. The EU is a key player in this evolution, with the potential for future regulatory measures to improve the efficiency of HDVs, a significant source of CO_2 emissions in the region.

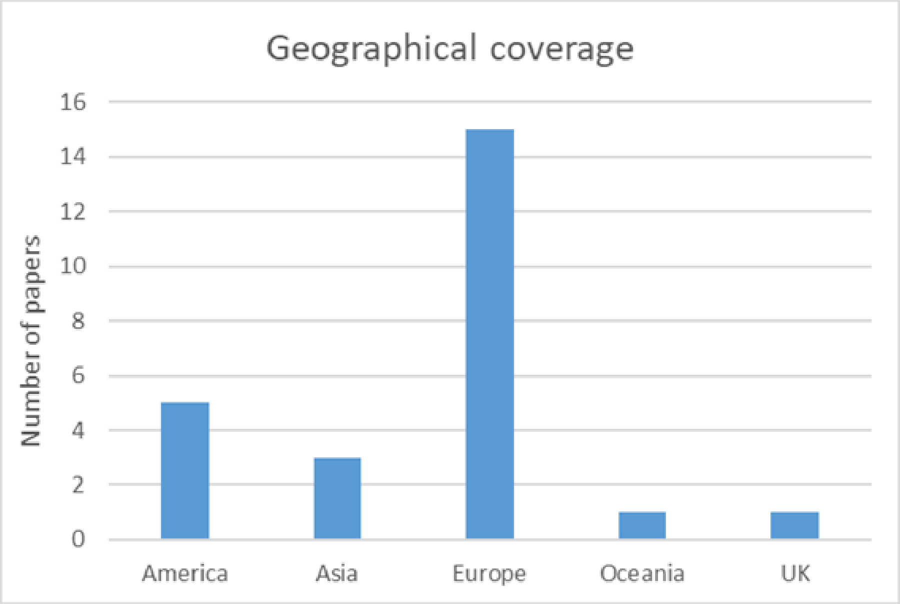


Figure 5: Geographical coverage in LCA investigated studies

2.2.3 Powertrain technologies

The literature review focused on three powertrain types: Internal combustion engine vehicles (ICEV), FCEV, and BEV with the aim of comparing data, methods, and assumptions. Figure 6 shows the number of publications considered for the literature review divided by powertrain type. The most studied powertrain type is BEV which reflects the current decarbonization trend in the transport sector.

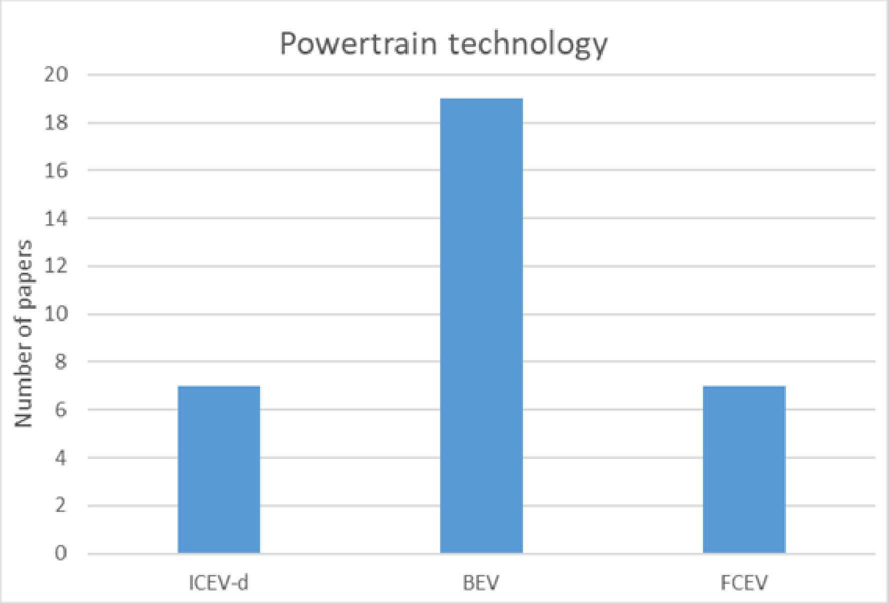


Figure 6: Powertrain technology in LCA investigated studies

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

2.2.4 Replicability

Figure 7 summarizes the number of papers in which LCI datasets are available. In an LCA study the availability of LCI datasets is a measure of the replicability of the study. Only 6 out of 24 studies have found to be replicable. Among these, 3 papers are based on Ecoinvent datasets, 1 is based on a mix of GREET and Ecoinvent datasets for vehicles, and 2 are based on the same data taken from GREET. Some papers are based on data from GREET representative of 2022, some are much older.

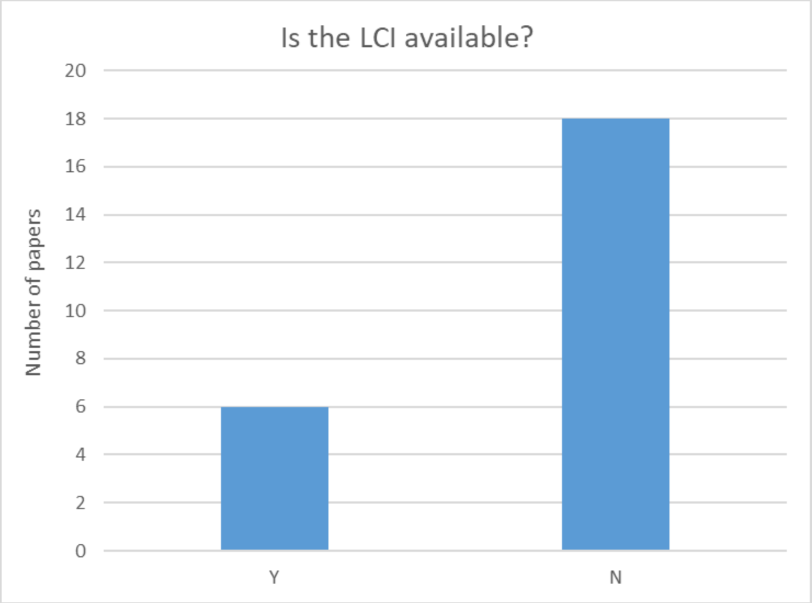


Figure 7: LCI available in LCA investigated studies.

2.2.5 Functional unit

The definition of a functional unit is a fundamental step of an LCA study for conducting meaningful comparisons and assessments. However, there is a lack of consensus and structure in the current FU definition framework, leading to variability in LCA results [14]. The ton-kilometer (ton*km) resulted as the predominant functional unit employed within the investigated LCA studies (Figure 8) and represents the payload of the goods transported multiplied by the lifetime of the vehicle in km.

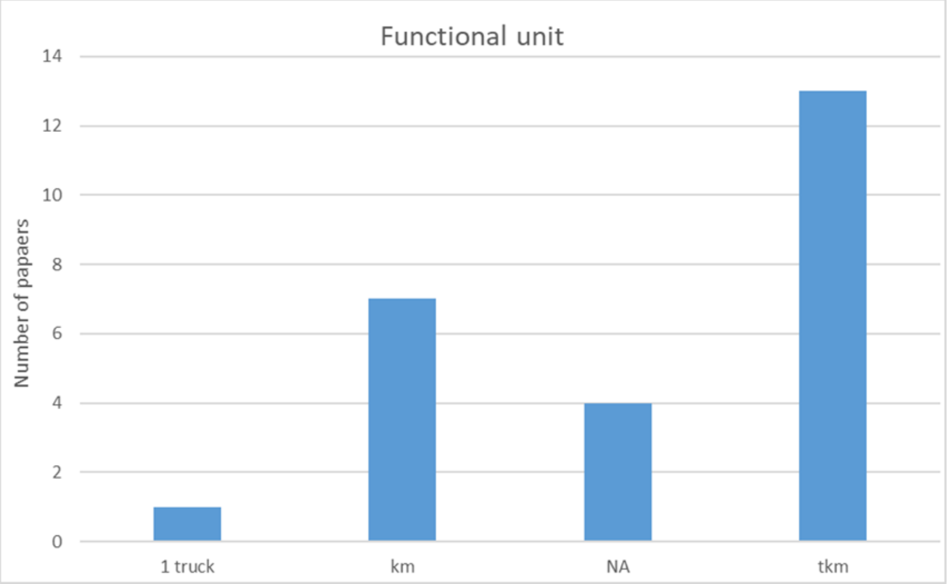


Figure 8: Functional unit in LCA investigated studies

2.2.6 System boundary

The system boundary definition is a critical phase in LCA studies, as it determines the unit processes to be included in the product system. This phase is necessary for a comprehensive understanding of a product's environmental impact, as it may encompass all life cycle stages, from raw materials acquisition to disposal, or not [15]. The selection of system boundaries in LCAs can significantly impact the results and conclusions of the assessment [16]. The system boundary choice is influenced by data availability and the study's goal.

The system boundary alternatives include the "gate-to-gate" approach, which only incorporates manufacturing data, the "cradle-to-gate" approach, which encompasses raw materials extraction up to the supplier transport, the "cradle-to-use" approach, which further integrates the evaluation of the use phase, and finally, the "cradle-to-grave" approach, which comprehensively includes the entire lifecycle of a product. The cradle-to-grave approach has been found as the most used among the investigated studies (Figure 9).

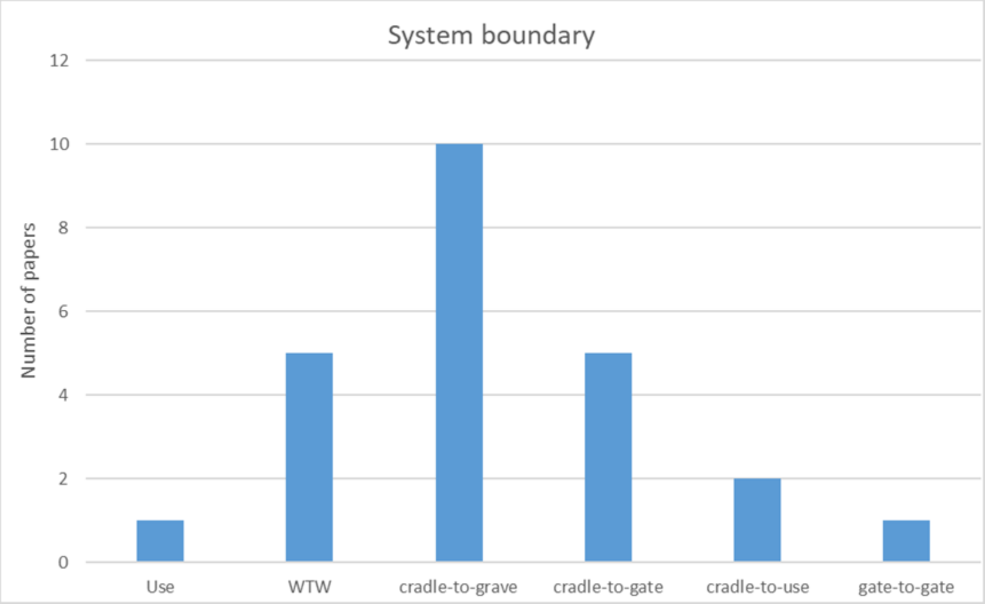


Figure 9: System boundary in LCA investigated studies

2.2.7 Annual mileage and vehicle lifetime

The incorporation of annual mileage in LCA studies is crucial for a more accurate assessment of the impacts, as it allows for the consideration of usage patterns and operational efficiency. Therefore, annual mileage directly influences factors such as fuel consumption and maintenance requirements, which are integral components of LCA calculations. Figure 10 shows the annual mileage considered in the investigated studies.

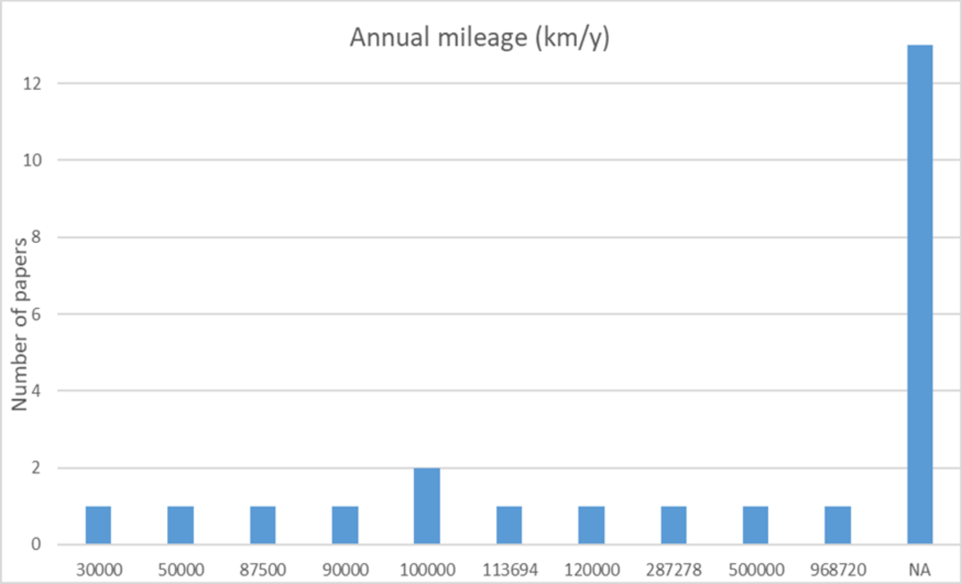


Figure 10: Annual mileage (km/y) in LCA investigated studies.

In the LCA field, the importance of considering the lifetime of a vehicle is widely recognized. Although the various scientific publications do not clearly state the units of measurement used, it is commonly acknowledged that the lifespan of a vehicle plays an important role in LCA analyses. Generally, the units of measurement used to quantify the life of a vehicle are consistent across studies, with years and kilometers being the most common (Figure 11, Figure 12).

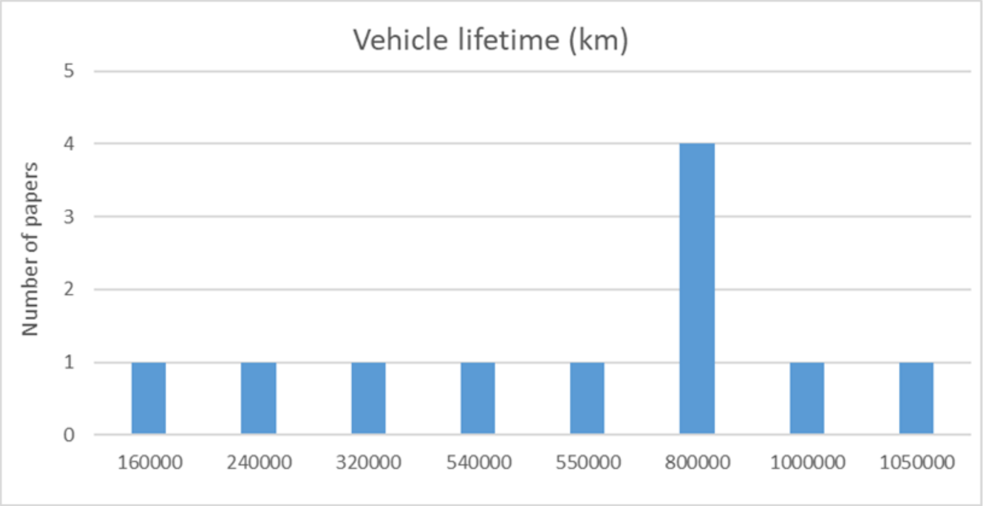


Figure 11: Vehicle lifetime (km) in LCA investigated studies

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

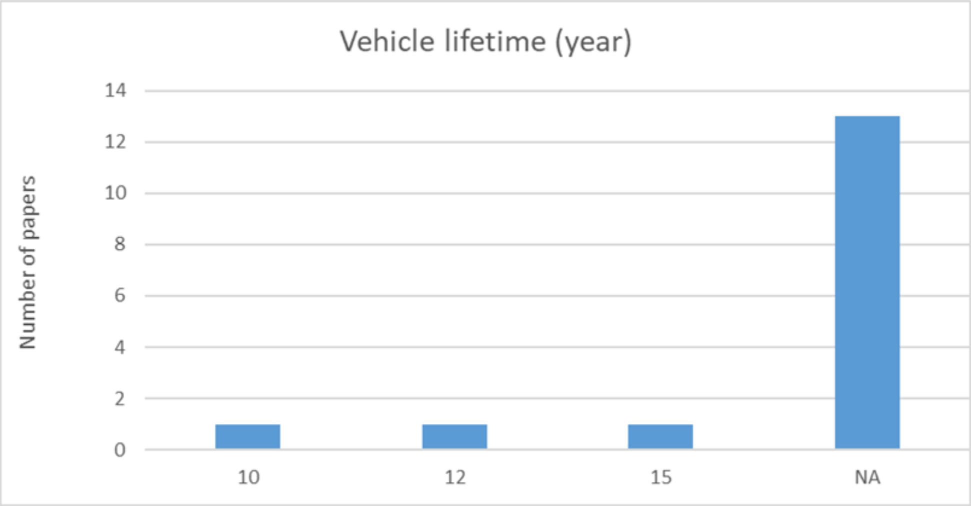


Figure 12: Vehicle lifetime (years) in LCA investigated studies

2.2.8 Software

The LCIA is the third phase of LCA. The LCIA is aimed at evaluating the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The LCIA phase also provides information for the life cycle interpretation phase [9]. The LCIA phase can be conducted using specific LCA software. The management of LCI data, which is critical for LCA, can be difficult because of the large amount of data. The adoption of specific LCA software can simplify and facilitate its management.

Figure 13 summarizes the results of the most used software in LCA studies. As the figure shows, the most widely used software are Simapro, OpenLCA, and Gabi. Some papers do not report the software used for the LCA study.

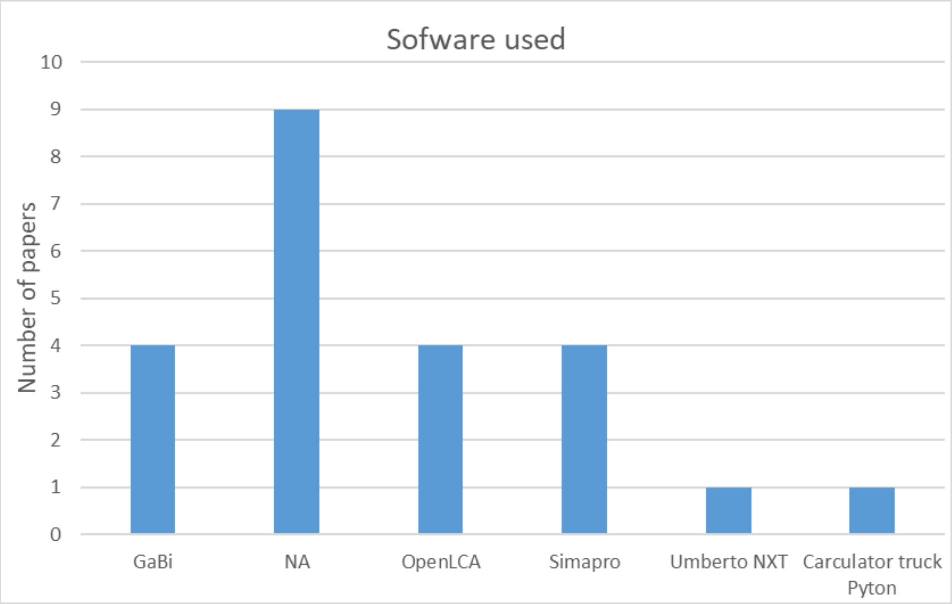


Figure 13: Software used in LCA investigated studies.

2.2.9 Database

The selection of a database is indeed a crucial aspect of LCA studies, as it provides essential information necessary for conducting comprehensive assessments. Despite its importance, the mention of the database used in LCA studies, may be limited or even absent in some papers (Figure 14, in the last column "NA"). The choice of database remains a critical consideration. It directly influences the reliability and credibility of the assessment, impacting the validity of conclusions drawn from the study. The Ecoinvent database is a widely used resource in the LCA studies (Figure 14). This database, developed by the Swiss Centre for Life Cycle Inventories, contains over 2500 background processes and follows quality guidelines to ensure data coherence [17].

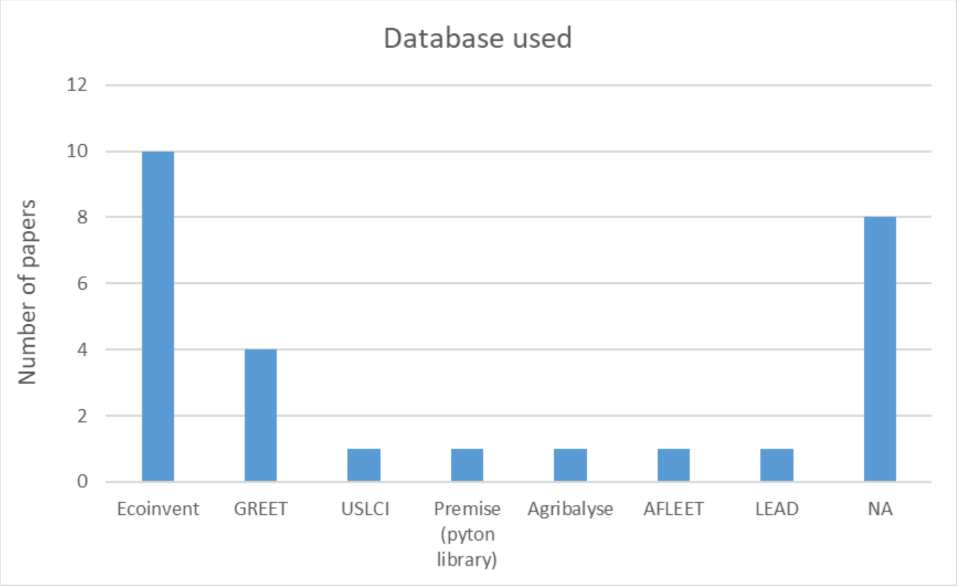


Figure 14: Database used in LCA investigated studies

2.2.10 Impact categories under scope and LCIA method

In LCA studies, several impact categories are evaluated to assess the environmental consequences of a product or process. Among these categories, one of the most widely used and crucial is Global Warming Potential (GWP). GWP is an indicator used to quantify greenhouse gas (GHG) emissions in terms of their equivalence to carbon dioxide (CO_2eq). GWP is particularly significant because it enables researchers and stakeholders to compare the potential climate change impacts of different emissions across various time horizons. By expressing emissions in CO_2eq, GWP facilitates a standardized metric that accounts for variations in the atmospheric lifetimes and radiative properties of different greenhouse gases.

In addition to GWP, several other impact categories are commonly evaluated in LCA studies, such as acidification potential, eutrophication potential, ozone depletion potential, human toxicity potential, resource depletion, etc. To achieve a thorough assessment of a product's environmental impact in LCA studies, it is essential to encompass a wide array of impact categories.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

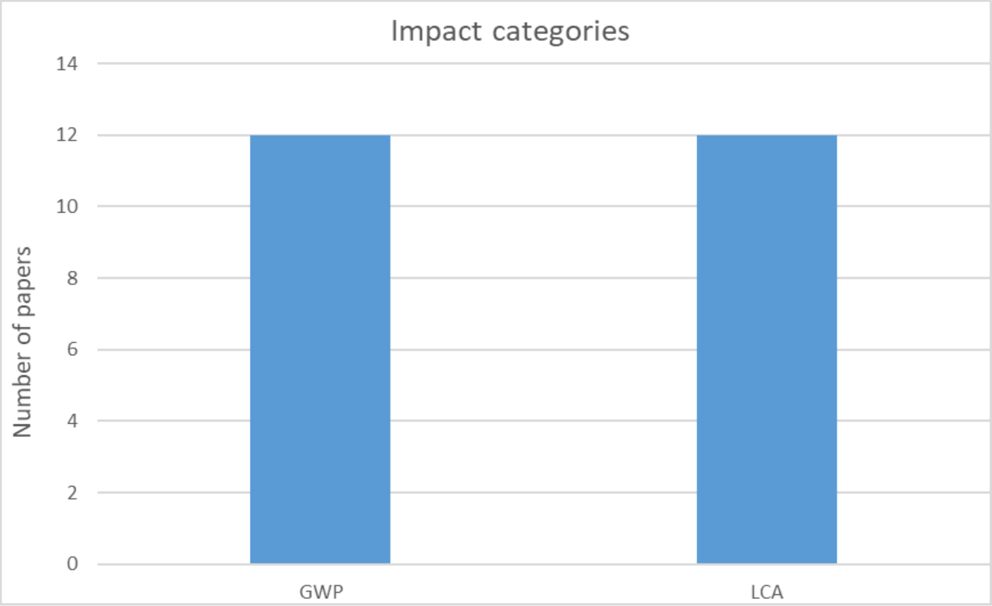


Figure 15: Impact categories in LCA investigated studies.

LCIA methods are used to evaluate the potential environmental impacts associated with a product or process throughout its life cycle. Besides the impact categories mentioned earlier, there are various LCIA methods used in LCA studies. Figure 16 shows a wide variety in the use of LCIA methods. The most widely used is Recipe 2016. The EF 3.0 method (which represents a revision of the Recipe 2016), also known as the Product Environmental Footprint method, was developed as part of the European Commission's initiative to establish Product Environmental Footprint Category Rules (PEFCR) and Sectoral Environmental Footprint Guidelines (SEFG) under the Product Environmental Footprint (PEF) initiative. The PEF initiative aims to harmonize the assessment of the environmental performance of products across the European Union.

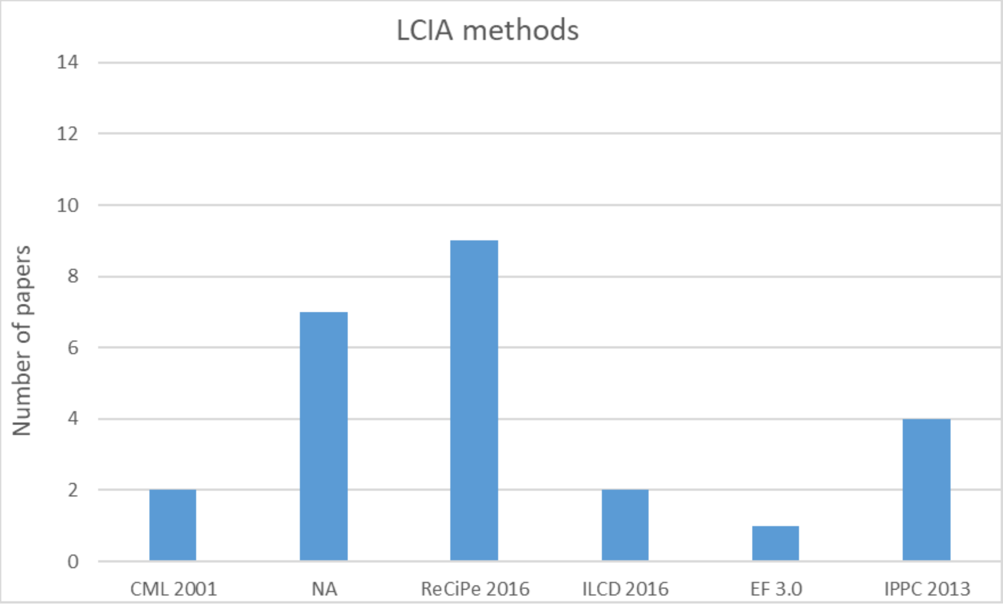


Figure 16: LCIA methods in LCA investigated studies.

2.2.11 Carbon Footprint Results

The calculation of the carbon footprint serves as a crucial outcome in environmental impact assessments, particularly for products. The carbon footprint quantifies the total amount of greenhouse gas emissions,

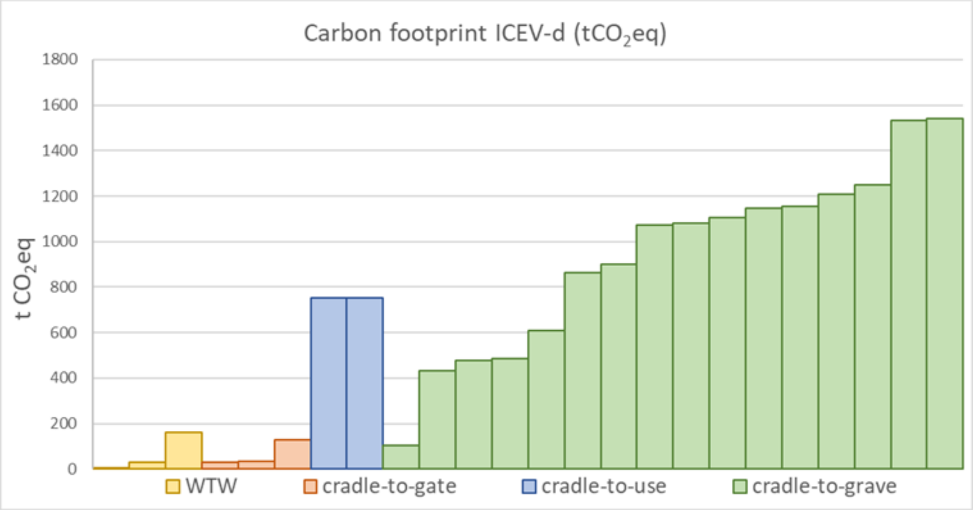
This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

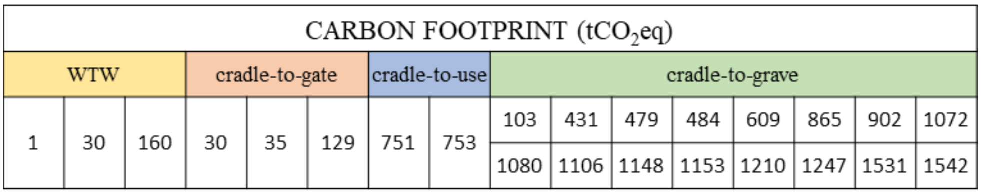
typically expressed in carbon dioxide equivalents (CO_2eq), associated with the entire life cycle of a product or service. This metric provides valuable insights into the environmental impact of a product, particularly in terms of its contribution to climate change.

To enhance comparability between different studies and products, the carbon footprint is often expressed in terms of a functional unit. The functional unit represents a quantifiable measure of the performance or functionality of the product or service being assessed. By standardizing the expression of the carbon footprint concerning the functional unit, stakeholders can more easily compare environmental performance across different products or processes, regardless of variations in scale, complexity, or other factors.

Within the automotive sector, various functional units are employed to compare carbon footprint results of HDVs, such as "per kilometer driven," "ton per kilometer," or "one truck" (Figure 21). However, the adoption of different functional units hinders the assessment and comparison of the environmental impact across different vehicle models or technologies. Figure 17 illustrates the carbon footprint values of diesel-powered HDVs, expressed in terms of tons of CO_2 equivalent per truck, based on literature studies [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]

The observed data exhibit significant variability, primarily due to the variation in the system boundary adopted. Most of the studies have assumed a cradle-to-grave boundary, so they comprise the entire life cycle from the raw materials extraction to the disposal. However, even when considering the same boundary, there is substantial variability in the data, which is likely caused by comparisons among vehicles of different classes (a detail frequently left unspecified in the examined papers).





CARBON FOOTPRINT (tCO_2eq)															
WTW			cradle-to-gate			cradle-to-use		cradle-to-grave							
1	30	160	30	35	129	751	753	103	431	479	484	609	865	902	1072
								1080	1106	1148	1153	1210	1247	1531	1542

Figure 17: Carbon footprint (t CO_2eq) for different system boundaries

2.2.12 LCA Literature Review Conclusions

In conclusion, according to the literature review, the vehicle class is never specified, whereas the objective of EMPOWER is to assess the impacts of VECTO group 9 vehicles. Also, available LCAs are based on secondary data and are not suitable for the baseline diesel truck because they could compromise the accuracy and quality of the assessment.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

The literature studies cannot be used for the baseline diesel truck because they are not representative of the EMPOWER project. Indeed, to ensure an accurate and high-quality LCA assessment, primary data are required. Therefore, primary data provided by IVG have been used for the baseline diesel truck assessment to ensure a better quality of the environmental assessment of trucks and to perform a more realistic comparison to ZE HDVs. The results of the literature review could be useful to represent how POLITO assumptions are in the existing literature and to validate the EMPOWER results.

3. Introduction to Total Cost of Ownership and literature review

3.1 Introduction to Total Cost of Ownership

In the business and technology field, particularly within the freight transport sector, decision-making processes are not as linear as they initially appear. The evaluation of an asset's true cost, exemplified here by a vehicle tasked with goods delivery, necessitates a holistic viewpoint. The metric of TCO surfaces as an indispensable tool, enabling decision-makers to formulate informed and sustainable choices.

TCO is a holistic approach to assess the complete financial impact of owning and operating an asset over its entire lifecycle [42]. This encompasses not only the upfront purchase price but also the ongoing costs associated with maintenance, operation, and any potential expenses [43], [44]. One key aspect of TCO is its emphasis on the entire lifecycle of the asset, the truck in the project aim. This perspective forces businesses to look beyond the initial acquisition cost and consider the expenses that will be incurred throughout its useful life, including maintenance, upgrades, and potential end-of-life costs. The starting point of TCO analysis is the purchase price. This includes not only the initial cost of acquisition but also any associated costs such as taxes, shipping, and installation fees. In the case of the truck under study, since the object under study is a vehicle, the purchase cost is the initial cost related to the acquisition of the vehicle.

Operating costs constitute a significant portion of TCO. These include expenses related to energy consumption (fuel consumption), preventive maintenance and repairs, and any consumables required for the proper functioning of the asset (e.g., urea consumption, lubricating oil, etc). Finally, the residual value is the value that the asset will have after the owning period considered [45]. A schematic view can be seen in the Figure 18.

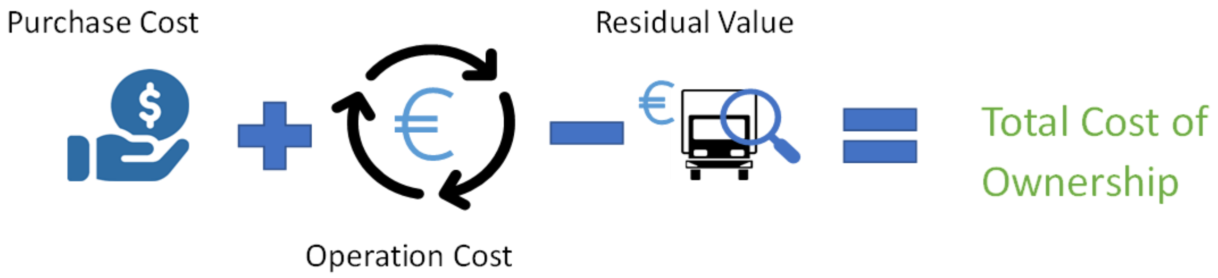


Figure 18-Total Cost of Ownership

Understanding these ongoing costs is crucial for a comprehensive TCO evaluation. By incorporating all relevant costs, TCO provides decision-makers with a more accurate picture of the financial implications of their choices. This, in turn, enables better-informed decision-making aligned with long-term business goals. TCO analysis helps identify potential risks and uncertainties associated with an investment. Understanding the full scope of costs allows businesses to develop strategies to mitigate risks and plan for contingencies. Considering the entire lifecycle of an asset promotes sustainability. By evaluating the economic impact, fleet operators can align their decisions with broader sustainability goals.

When choosing between different vehicle technologies, TCO becomes an indispensable tool, aiding customers in navigating the intricacies of evolving technologies and market dynamics [46]. It enables them to pinpoint the most cost-effective, aligning with their specific needs and preferences.

One aspect that is crucial to highlight is the time value of money and therefore the need to actualize cash flows. The concept is that a unit of money today is worth more than a unit of money in the future. That is because the investors can invest the money elsewhere to gain a profit from it. The easiest way to make an example is to note that if an investor can obtain a 5% in an obligation or a controlled fund the unit of money today would be worth 1.05 times a year from today.

The determination of the interest rate on savings is contingent upon two primary factors when assured of repayment by the borrower. Firstly, inflation introduces a diminution in the purchasing power of a unit of money over time, prompting the necessity for an interest rate to offset the resultant loss in real value. Secondly, an inherent preference for immediate consumption over future consumption necessitates compensation in the form of an interest rate to induce individuals to defer spending. This compensatory interest rate is denoted as the real interest rate, which varies based on individual preferences for current consumption.

In situations where the assured return on savings is subject to uncertainty, an additional component in the form of a premium for uncertainty is introduced. This premium serves as compensation for the increased risk associated with uncertain returns, with higher uncertainty warranting a commensurately higher premium.

In summary, the return on investment, when considering the deployment of a Euro elsewhere, is comprised of three integral components: the anticipated inflation rate, a real interest rate, and a premium for uncertainty. The fundamental concept underpinning the time value of money is rooted in the potential to invest money elsewhere to yield returns, commonly referred to as a discount rate [47].

In conclusion, TCO is a powerful tool that transcends traditional financial assessments. It EMPOWERs investors to make decisions that are not only financially sound in the short term but also sustainable and strategic over the long term. Embracing TCO as a guiding principle can lead to more resilient and successful companies in today's dynamic and complex business environment.

3.2 Literature Review

The EMPOWER European project has set an ambitious target: to reach TCO parity by 2029 between emerging technologies (BEV and FCEV) and the baseline diesel-powered truck of 2020. In terms of the deliverable content, the objective is to derive a state-of-the-art baseline from existing literature that accurately represents the 2020 ICE truck. This baseline will serve as a benchmark for the two demonstrators that will be developed throughout the project. To achieve this, an extensive literature review was conducted with this specific aim in mind. This approach ensures that our starting point is grounded in the most recent and relevant research, setting the stage for meaningful comparisons and evaluations as the project progresses.

The literature review process was initiated with a systematic search across three prominent academic databases: Scopus, ScienceDirect, and Google Scholar. The search strategy was designed to be comprehensive and targeted; the final choice fell on utilizing two sets of keywords: ‘hdv AND tco’ and ‘tco AND truck’. This approach was chosen to ensure the inclusion of all potentially relevant literature on the TCO of heavy-duty vehicles.

The initial search yielded a substantial number of papers, totaling 1587. These were distributed across the databases as follows: Scopus contributed with 35 papers, ScienceDirect provided 731, and Google Scholar accounted for the remaining 608.

To effectively manage the extensive volume of literature, a stringent filtration process was put into action. This process was designed to ensure that only the most relevant and accessible papers were included in the review.

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

The initial phase of this process involved verifying the availability of the full text of the papers. Given the importance of a comprehensive review, it was crucial to have access to the complete content of each paper. This step ensured that no potentially significant information was overlooked due to limited access.

Following this, the relevance of each paper to the research topic was assessed. This was a critical step in the filtration process, as it ensured that the review remained focused and pertinent to the research topic. The assessment was carried out by meticulously reviewing the abstracts of the papers. In cases where the abstract did not provide sufficient information, the introduction and conclusion sections were also examined. This thorough review allowed for a precise determination of each paper's applicability to the specific question under analysis.

Simultaneously, a check for duplicates was conducted. This was an essential step, as it was observed that the same papers were often found across different academic databases. By ensuring that each paper was only counted once, this step prevented any potential skewing of the data due to duplicate entries.

This filtration process significantly reduced the number of papers, resulting in a refined set of 44 documents. A graphical description of the workflow is provided in the Figure 19. These papers were then subjected to an in-depth review. Each paper was read in its entirety, and the key findings, methodologies, and conclusions were extracted and analyzed. It is important to underline that not every document is a TCO study/assessment, the majority are because some document is considered to give the possibility to analyse in depth the breakdown cost in the transport sector.

The review was guided by the specific scope and goal of the task, which was to gain a comprehensive understanding of the TCO of a heavy-duty vehicle that should describe the state of the art in freight transport. This ensured that the review remained focused and relevant, while also being exhaustive.

Upon completion of the review, the results were extracted and synthesized. These results were further visualized using graphs, providing a clear and intuitive representation of the findings. This not only facilitated a better understanding of the data but also allowed for easier comparison and analysis.

This meticulous and systematic approach to the literature review ensured the inclusion of all relevant literature, providing a robust and comprehensive foundation for the next steps. The use of graphical representations further enhanced the accessibility and comprehensibility of the findings, making them readily available for further analysis and interpretation.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

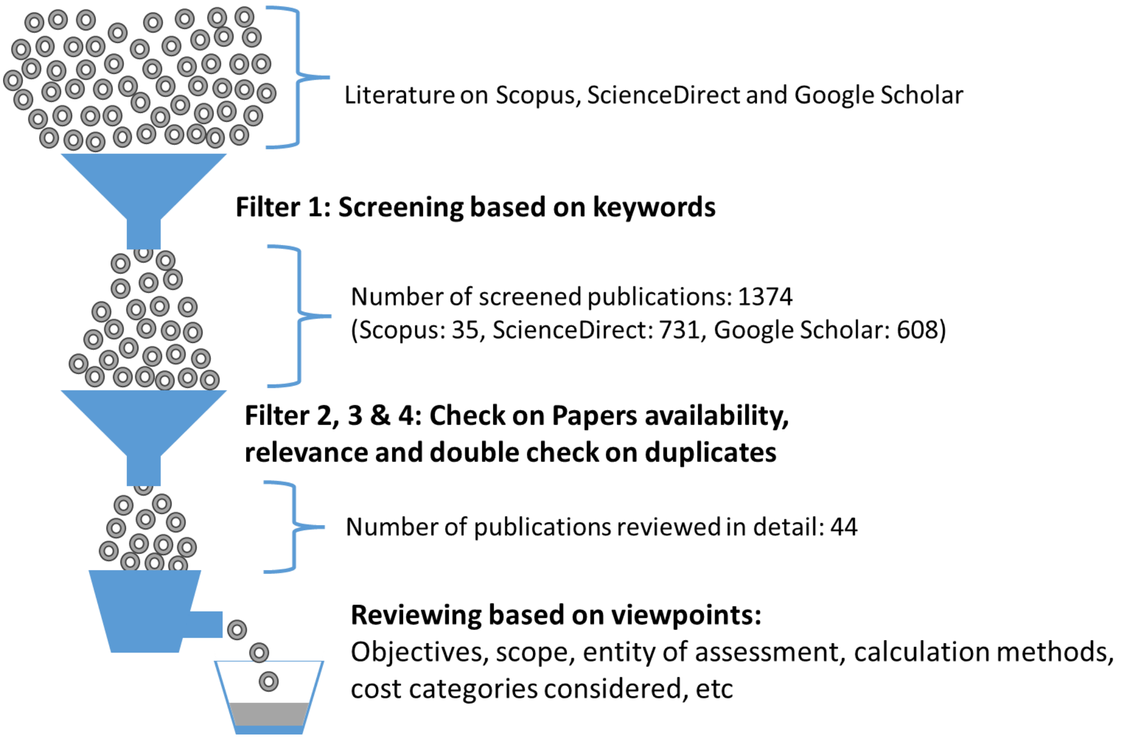


Figure 19 - Literature Review Workflow

3.2.1 Year of Publication

In the rapidly evolving field of technology in the transport sector, it is crucial to focus on recent research and studies, specifically papers and technical reports published within the last five years (2017-2023). This is particularly relevant when examining the TCO of Heavy-Duty Trucks, where conventional Internal Combustion Engines (ICE) are being compared with emerging technologies like Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV). The swift pace of technological advancements necessitates this focus on the most current research. It is noteworthy that most of these papers have been published since 2020, underscoring a surge in interest among researchers and stakeholders in this specific topic as clearly shown in Figure 20. Indeed, this trend not only signifies the increasing acknowledgment of the role and potential influence of these new technologies on the TCO of Heavy-Duty Trucks, but it also highlights the recent regulations, especially in the European Union, that are steering towards a decarbonization of the transport sector [48], [49].

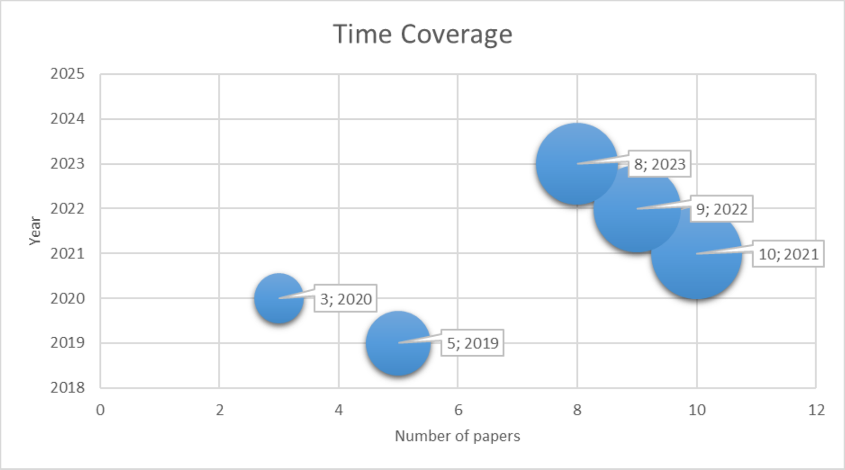


Figure 20-Year of Publication

3.2.2 Functional Unit

In TCO studies, the Functional Unit (FU) assumes a pivotal role. It serves to quantify the function of a product or service, thereby providing a reference basis for the computation of the total cost. The FU offers a standard measure that facilitates the comparison of different technologies with varying costs, ensuring that such comparisons and assessments are fair, relevant, and meaningful.

Upon analyzing various TCO studies, it becomes evident that the majority present the TCO in monetary units, without the selection of a specific functional unit [45], [50], [51], [52], [53], [54], [55], [56], [57], etc. As delineated in Figure 21, an analysis of over twenty studies reveals that no functional unit is chosen. A limited number of studies opt for the distance unit (kilometers for studies conducted in Europe and miles for those in the USA or UK) [58], [59], [60], [61], [62], [63], [64], etc., while a few studies do not report it at all [65]. Notably, none of the studies report the functional unit of distance per mass (km*kg or km*t), which is the unit proposed in the project proposal.

Given that the project pertains to freight transport, the volume of goods transported is a crucial factor to assess and consider. To align the two assessments, both LCA and TCO should adopt the same functional unit, in this case, km*t. This alignment is essential to ensure consistency and comparability across the assessments.

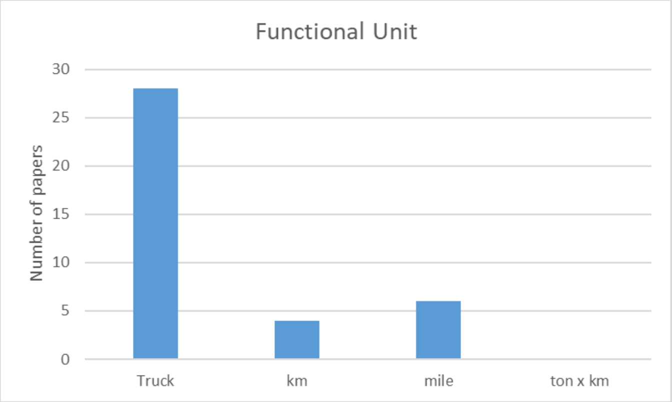


Figure 21-Functional Unit

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

3.2.3 Vehicle Lifetime (year)

The vehicle's lifetime is a critical factor to consider when calculating the TCO, which includes all costs incurred throughout the vehicle's lifespan. The choice of a specific lifetime should be as accurate as possible, reflecting the state of the art and the fleet operator's real needs. This is because a longer or shorter lifespan can significantly alter the results due to the costs associated with vehicle operations, such as fuel, driver, and maintenance costs.

From the literature review, as suggested by the Figure 22, it becomes clear that there is no universally agreed-upon standard for the lifetime of vehicles, especially in the heavy-duty sector. Unlike passenger cars, heavy-duty vehicles' lifespans are highly task dependent. For instance:

- Long-haul trucking vehicles, characterized by extensive highway driving and meticulous maintenance, commonly boast lifespans ranging from 500,000 to 1,000,000 kilometers. This notion is corroborated by the Euro 7 proposal [66], which, if approved, mandates a minimum manufacturer guarantee of 700,000 kilometers.
- Urban freight shipping vehicles, navigating through congested urban areas, and enduring frequent stops, typically sustain lifespans spanning from 300,000 to 500,000 kilometers. This aligns with the Euro 7 proposal[66], which establishes a minimum lifespan requirement of 400,000 kilometers for such vehicles.

Several studies consider the first ownership period [45], [56], [61], [65], [67], [68], [69], typically five years. Others use the manufacturer's guaranteed lifetime or the actual lifetime of a truck [70]. The draft of the EURO7 proposal also provides a minimum lifetime in terms of distance traveled [66], which is closely tied to the heavy-duty vehicle category/group. This diversity in approaches underscores the complexity of defining a vehicle's lifetime.

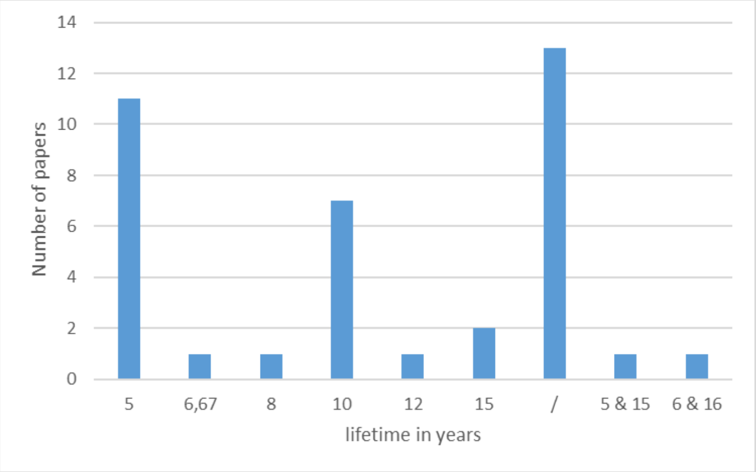


Figure 22-Vehicle Lifetime (years)

3.2.4 Yearly mileage (km)

The study's yearly mileage assumption is a crucial factor in all cost assessment studies. As depicted in the accompanying Figure, there is a significant variation in this aspect in the studies analysed, primarily because a truck's yearly mileage is intrinsically tied to its classification and, consequently, its designated mission. For example, urban delivery trucks are typically characterized by shorter yearly mileage, while long-haul trucks often exhibit longer yearly mileage. This pattern, confirmed by various literature studies (e.g.[46], [50], [71]), suggests that the selected yearly mileage is contingent upon the truck's mission or the fleet operator's needs. In 2019, the European Commission attempted to give a standard value of annual mileage for trucks as part of a regulation aimed at reducing carbon dioxide emissions in the heavy-duty transport sector. As outlined in table 4 of the annex I [48], the vehicle's mileage is associated with its group and specific mission, here reported for clarity.

Table 2-Annual mileages

Vehicle sub-group	Annual mileage (km)
4-UD	60,000
4-RD	78,000
4-LH	98,000
5-RD	78,000
5-LH	116,000
9-RD	73,000
9-LH	108,000
10-RD	68,000
10-LH	107,000

Interestingly, most of the studies do not report the annual mileage. This is primarily because these studies prefer to express the vehicle's lifetime in terms of total distance covered or total years of operation, resulting in a lack of detailed information about the annual mission. One particular study [70] opted for a more dynamic approach, choosing the distance per year as a function of the year of use instead of a fixed value. While this method can potentially offer more accurate results, it necessitates reliable primary data from the fleet operator to fit the function used in the study, which may become a hard challenge.

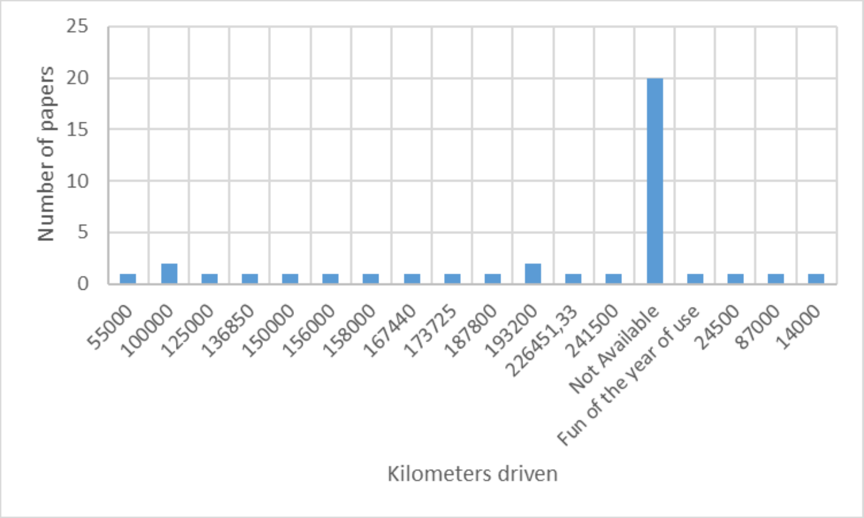


Figure 23-Yearly Mileage

3.2.5 Technologies Considered

In the realm of technologies examined in the reviewed studies, it is noteworthy that none of these studies consider the TCO for standalone diesel-powered internal combustion engines. The primary focus of each study is a comparative analysis between conventional methods of goods transportation and emerging technologies.

A significant number of these studies concentrate on battery electric vehicles [50], [52], [54], [58], [59], [60], [61], [62], [63], [64], [68], [69], [70], [71], [72], [73], [74], [75], [76] (Figure 24), primarily due to its more established status compared to fuel cell electric vehicles. This maturity of technology facilitates a more straightforward estimation of costs associated with both the operation and acquisition of trucks.

However, there has been a recent surge in studies focusing on fuel-cell electric vehicles [45], [50], [53], [55], [58], [60], [64], [65], [69], [70], [71], [77], [78], [79], primarily attributed to their shorter refueling time and the possibility of traveling longer distances. Despite being a more expensive technology, fuel cell electric vehicles are increasingly being evaluated, especially for long-haul missions that involve extensive distances. This trend underscores the growing interest in fuel-cell electric vehicles in the transportation sector.

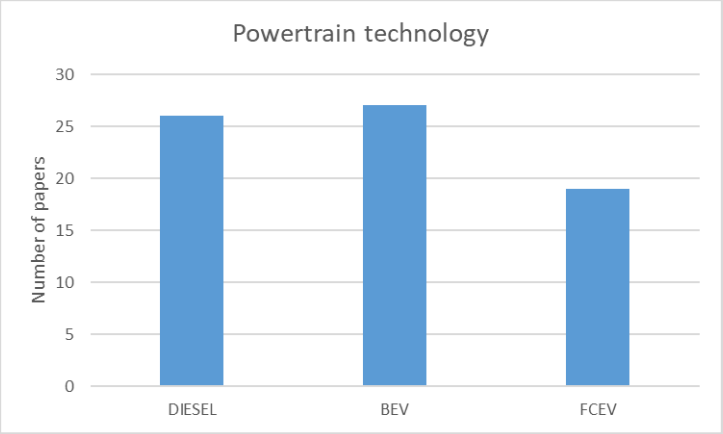


Figure 24-Technologies Considered

3.2.6 European Truck Group

In the pursuit of establishing a reliable baseline for diesel-powered trucks, particularly those belonging to the VECTO Group 9, it is imperative to scrutinize the categories and groups selected in existing studies. However, the lack of clarity in this area is a significant obstacle.

Regrettably, most of these studies do not specify the truck category or group. This omission is understandable in non-European studies, as they have no obligation to define a group that is only relevant within Europe. However, even European studies often neglect to provide this information. For instance, several studies allude to long-haul applications but fail to incorporate crucial details such as the truck weight. This omission hinders the reader’s understanding of the vehicle category under discussion. Given that our focus is on heavy-duty vehicles, it is essential to specify whether we are referring to categories N2 or N3.

The inclusion of such details would significantly enhance the comprehensibility and relevance of these studies.

Only a handful of studies disclose the European truck group under consideration [51], [61], [73], and even fewer details about the specific mission assessed [65], [65], [77]. Notably, none of these studies have investigated the VECTO Group 9, which is the focus of the EMPOWER project.

Given that each group has its unique specifications, extracting a reliable baseline from the literature becomes increasingly challenging when no studies have explored this specific VECTO group.

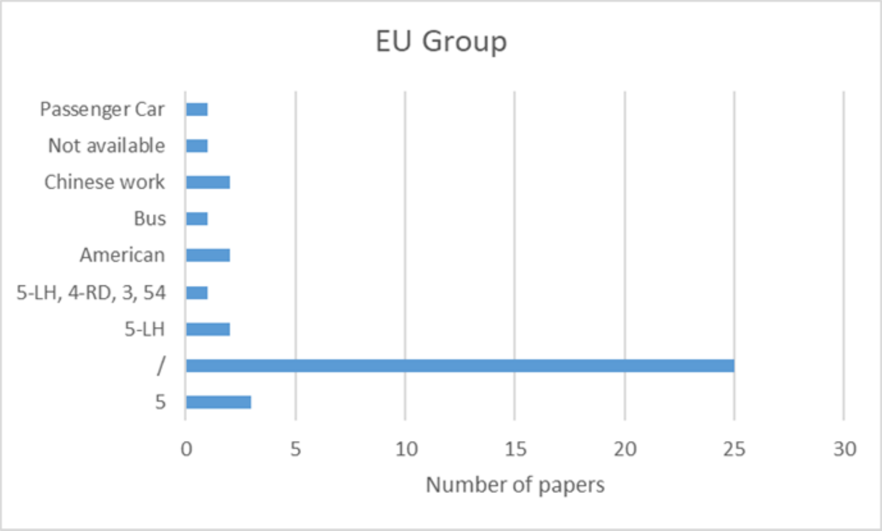


Figure 25-EU Truck Group (accordingly VECTO)

3.2.7 Delivery Mission

The selection of a specific mission by the researcher for the TCO delivery appears to lack sufficient clarity. This assertion is substantiated by the fact that an excess of thirty studies neglect to reference the specific delivery mission undertaken by the truck under investigation (Figure 26). A limited number of these studies explore Long Haulage [65], [65], [73], [77], [78], [80], with a mere duo focusing on Regional and Urban Distribution [65]. This oversight introduces complexity to the establishment of a reliable baseline. Following the stipulations of the project proposal and deliverable D1.1, the analysis is required to incorporate two distinct baselines - one about regional distribution and another about long-haul distribution. Therefore, it

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

becomes imperative that the specific baseline diesel truck is meticulously tailored to align with the directives of the project proposal.

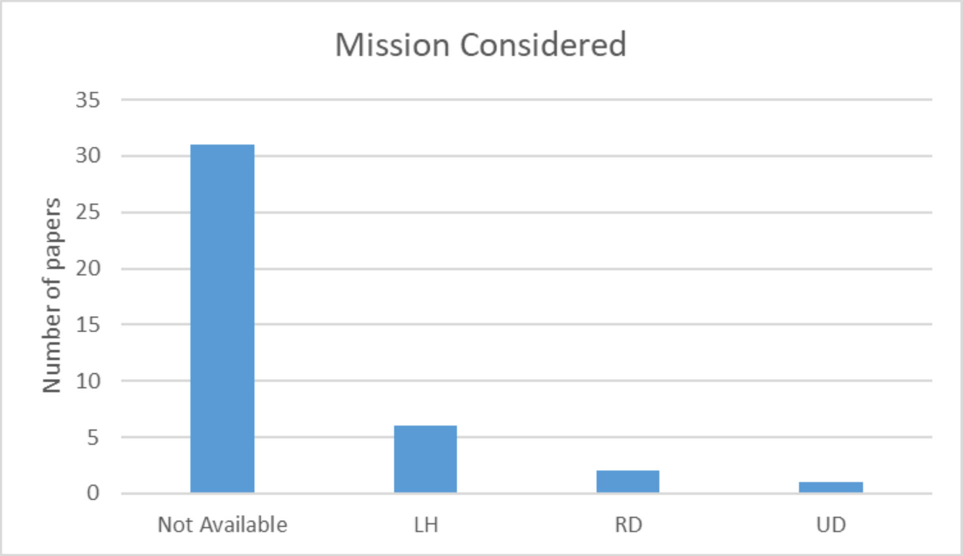


Figure 26-Delivery Mission

3.2.8 Discount Rate

Indeed, the discount rate is a pivotal concept in both finance and economics. It serves two primary roles:

- Time Value of Money: The discount rate embodies the principle of the time value of money, which posits that a unit of currency today is worth more than the same unit in the future. This is attributed to the potential of today's money to be invested and generate returns, thereby yielding a greater amount in the future.
- Risk and Opportunity Cost: The discount rate also encapsulates the risk associated with an investment and the opportunity cost for a firm. In essence, it represents the return that could have been accrued from an alternative investment of equivalent risk. This is frequently referred to as the "hurdle rate," signifying the minimum rate of return required for an investment to be deemed worthwhile.

In the context of the TCO or economic evaluation of a product, the discount rate is employed to discount future cash flows to present value. This allows for a more accurate assessment of the investment's value today, considering future expenditure.

Upon reviewing the literature, it is observed that most of the studies do not incorporate any discount rate. Consequently, these studies overlook critical financial considerations such as the time value of money and opportunity cost. Instead, they evaluate the TCO by summing all costs incurred throughout the truck's lifecycle.

However, a subset of these studies does consider a discount rate, as illustrated in Figure 27. It is noteworthy that these studies predominantly select a discount rate between 7% and 10%. This choice is likely influenced by the fact that these studies examine new technologies, which inherently carry a relatively higher

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

investment risk. This observation underscores the importance of incorporating a discount rate when assessing the TCO, particularly when evaluating investments in new technologies.

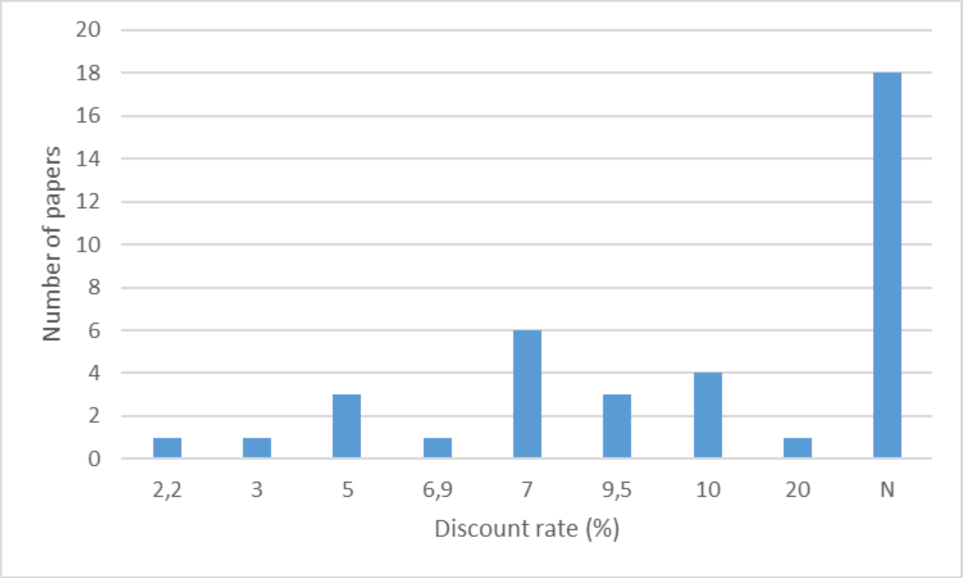


Figure 27-Discount Rate Chosen (%)

3.2.9 Inflation Rate

A significant proportion of the research does not account for price inflation, as illustrated in Figure 28. This is evident in over thirty studies where it is observed that the researchers did not incorporate any references to inflation. After analyzing the results, it becomes apparent that inflation was not factored into these studies. A small number of studies did consider the inflation rate [56], [70], [75], however, all of them assumed a fixed value for the inflation rate. The basis for this fixed value varied, with some studies choosing it arbitrarily, while others derived it from the average inflation rate of previous years.

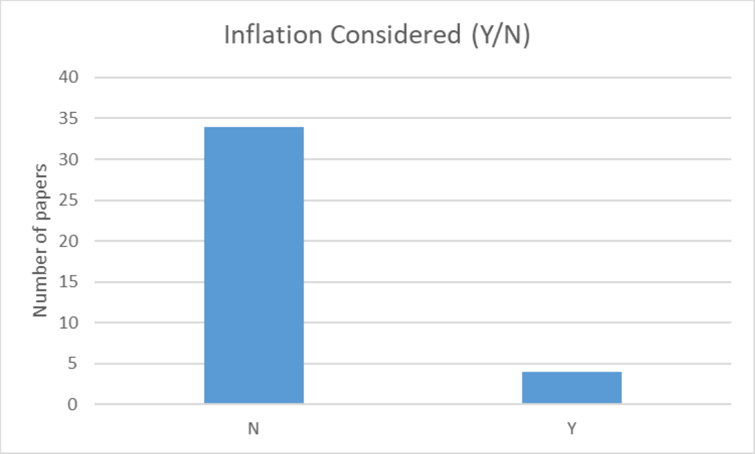


Figure 28-Is the inflation rate considered?

3.2.10 Battery replacement

Moving to technical considerations, the literature review reveals that the majority of studies do not account for battery replacement in heavy-duty vehicles during the period under review. Indeed, only a handful

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

contemplate the prospect of battery replacement during the operational lifespan of the truck [50], [56]. One study, in particular, considers battery replacement contingent on the scenario under consideration, factoring in two potential vehicle lifetimes and positing battery replacement for the longer one [54].

As evidenced in Figure 8, most studies omit this information. However, an analysis of the results suggests that when battery replacement is not explicitly addressed, it is typically not considered over the entire life cycle of the truck. Currently, there are no minimum requirements for battery durability for heavy-duty vehicles. A technical requirement has been published for passenger cars, stipulating a minimum state of certificate energy (SOCE) up to 160,000 km [81].

Concerning heavy-duty vehicles, a working group has been established to address this issue [82], given the increasing prevalence of zero-emissions vehicles in the heavy-duty market and the consequent need for regulation. In the absence of specific regulations on this matter, it may be most prudent to present various scenarios that illustrate the range of possibilities over the entire lifespan of the truck. This approach ensures comprehensive consideration of all potential outcomes.

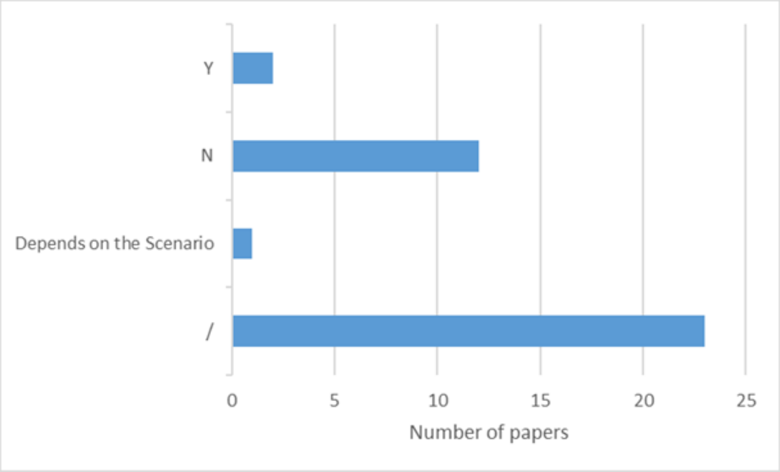


Figure 29-Battery replacement throughout the vehicle's life

3.2.11 Fuel Cell replacement

Fuel Cell replacement is something that is rarely considered in literature. Only two studies accounted for Fuel Cell replacement during the whole life cycle of the heavy-duty vehicle [50], [70].

Given the essential role of fuel cells in powering these vehicles, neglecting to account for their replacement needs could result in inaccuracies in cost estimates, operational planning, and assessments of environmental impact. Furthermore, the scarcity of TCO models incorporating fuel cell replacement underscores the necessity for further investigation and analysis in this field. It is crucial to understand the factors influencing fuel cell lifespan, the optimal timing for replacement, and the associated costs. Such understanding is vital for informing sustainable fleet management practices and promoting the widespread adoption of fuel cell technology in the heavy-duty vehicle sector.

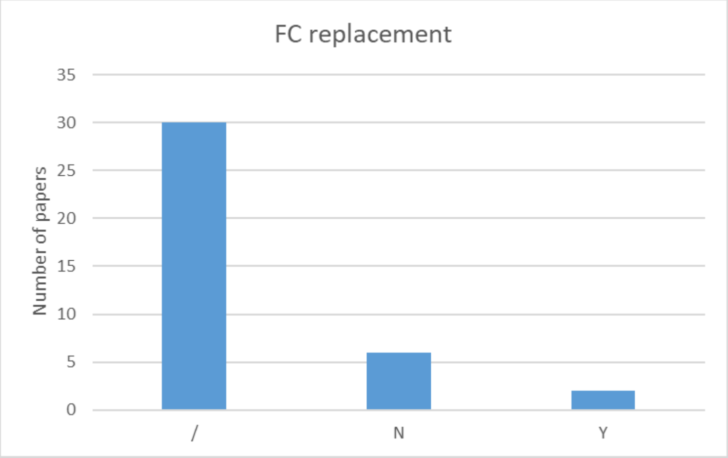


Figure 30-Fuel Cell replacement throughout the vehicle's life

3.2.12 Literature Review Conclusions

In conclusion, it is of paramount importance to underscore that the exhaustive literature review does not yield a reliable baseline that could be efficaciously employed as a benchmark for the two demonstrator trucks (BEV and FCEV) that are presently in the developmental phase as an integral part of this project.

This observation accentuates the inherent challenges associated with extracting pertinent information from secondary sources, especially when the subject matter pertains to not enough studied fields. The dynamic nature of the field coupled with the specificity of the project's requirements necessitates a more bespoke approach to the establishment of a baseline.

In response to these findings, a strategic decision has been made to pivot the TCO assessment focus towards primary data. This decision is being carried out to ensure the accuracy and relevance of the baseline data. By concentrating on primary data, it can be ensured that the baseline is not only reliable, but it is the best and fair comparison with the demonstrators developed in the EMPOWER project.

Consequently, undertake an assessment of two baseline diesel trucks from the MY2020 range provided by the IVECO manufacturer. These baselines will be established exclusively using primary data, thereby ensuring that they accurately mirror the current state of diesel technology. Coupled with the primary data provided by the IVECO manufacturer, a TCO model to best describe in detail the sum of the costs occurring during the truck's life is developed, trying to consider each cost that can occur during the truck's full life cycle.

This methodological approach will not only equip us with a more reliable baseline but also guarantee the highest possible degree of comparability between the two trucks equipped with novel technology and the MY2020 baselines. By adopting this approach, we aim to facilitate a more precise and meaningful comparison, thereby contributing significantly to the successful development and evaluation of the Battery Electric Vehicle and Fuel Cell Electric Vehicle trucks.

4. Baseline identification

Two baseline models were selected for evaluation after an extensive review of the literature. These models are used for regional and long-haul distributions. Despite having the same vehicle architectures, these two baselines have very different configurations. Therefore, both baselines were chosen for assessment, to provide two benchmarks for a fair and more scientific comparison with the two new demonstrators against the diesel benchmark.

Both baselines belong to the VECTO group 9. VECTO is a simulation tool developed by the European Commission. It calculates CO_2 emissions and fuel consumption from HDVs such as trucks, buses, and coaches with a GVW above 3500 kg. Trucks in VECTO group 9 are characterized by their axle and chassis configuration. Specifically, a group 9 truck has a 6x2 axle configuration and a rigid chassis. This means it has three axle wheels, one of which is intended to distribute power.

The regional baseline has a day cab because it is conceived as it is used only during the day. It is slightly different from the length foreseen for the EMPOWER demonstrator which will include a high number of batteries between rear and front axles. The gross vehicle weight has been set at 26 tons with full pneumatic suspension (mechanical suspensions are also suitable with a maximum axle weight of 9 tons).

The baseline for the long-haul mission has a sleeper cab because it will be used for international or long-distance delivery. The wheelbase of the long-haul truck is longer with respect to the regional, and the configuration includes a trailer, raising the gross vehicle weight to a gross combination weight of 40 tonnes. The two baseline trucks are different also because they have different powertrains due to the different missions. The long-haul truck requires more power compared to the regional distribution truck. In case of zero-emissions vehicle, the maximum authorized weights shall be increased by 2 tonnes, accordingly to Council Directive 96/53/EC [83]

Table 3 Main technical parameters of the two baseline vehicles and demonstrators

	Diesel RD	**Diesel LH**	**Battery-electric RD**	**FC-electric LH**
C-GVW[1]	40 tonnes	40 tonnes	Diesel + 2 tonnes	Diesel + 2 tonnes
Rigid truck axle configuration	6x2	6x2	6x2	6x2
Powertrain rated power	268 kW/360 CV	343 kW/460 CV	/	/
Fuel Cell rated power	/	/	/	/
Battery nominal energy	/	/	7 battery packs	2 battery packs
H2 Tank	/	/	/	73 kg
Transmission	12 speeds	12 speeds	2 speeds	2 speeds
Maximum uncharged range	/	/	400 km	750 km

[1] Combined Gross Vehicle Weight (C-GVW) comprises both vehicle and trailer weights.

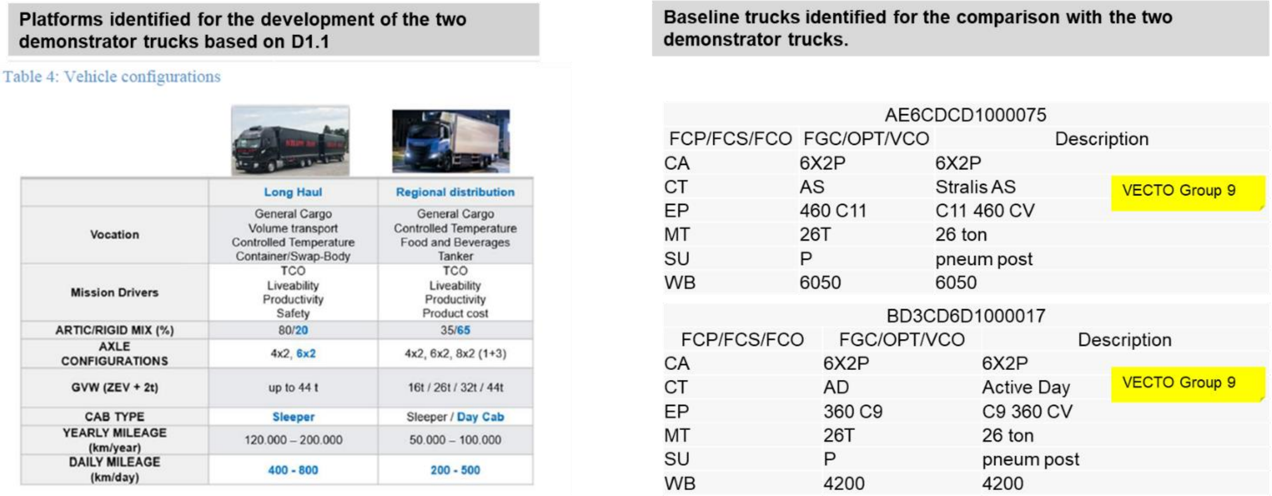
5. Shared assumptions between LCA and TCO

The FU is the reference payload multiplied by the vehicle lifetime measured in ton-kilometre (ton*km). The same FU has been chosen for both the LCA and TCO to align the environmental and economic assessments. The reason for this selection is that the ton-kilometre represents the core function of the products under study, intended to be used for freight transport. In fact, the shift towards ZE HDVs may imply an increase in the Mass in Running Order (MRO) and a decrease in the maximum payload against the diesel baselines. This ensures a fair comparison across different freight transport technologies. For reference payload, 13.4 tons has been assumed for the baselines based on the Euro7 draft for heavy vehicles. For the vehicle lifetime, 700,000 km has been assumed for all vehicles based on the Euro7 draft for heavy vehicles.

6. LCA model

The LCA models of the two baselines and the preliminary evaluation of the EMPOWER demonstrators have been carried out by the POLITO with the kind contribution of all project partners. POLITO has used a well-developed, cutting-edge LCA methodology, developed in collaboration with IVG in previous works and already tested on a case study. The methodology was originally designed for conducting comprehensive LCAs of light-duty commercial vehicles while, in EMPOWER, POLITO is extending the methodology to heavy-duty vehicles.

To ensure comparability, reliability, and accuracy with the truck demonstrators that will be developed in EMPOWER, two (and not one) diesel trucks have been considered to depict the state-of-the-art baselines (one for regional and one for long-haul distributions). The LCA of the baselines is not limited to the investigation of the literature studies, but two IVG-specific VPs have been identified as state-of-the-art baseline diesel trucks (Figure 31) and the LCA models of the two baseline vehicles have been developed from scratch based on IVG company-specific data.



Platforms identified for the development of the two demonstrator trucks based on D1.1

Table 4: Vehicle configurations

	Long Haul	Regional distribution
Vocation	General Cargo Volume transport Controlled Temperature Container/Swap-Body	General Cargo Controlled Temperature Food and Beverages Tanker
Mission Drivers	TCO Liveability Productivity Safety	TCO Liveability Productivity Product cost
ARTIC/RIGID MIX (%)	80/**20**	35/**65**
AXLE CONFIGURATIONS	4x2, **6x2**	4x2, 6x2, 8x2 (1+3)
GVW (ZEV + 2t)	up to 44 t	16t / 26t / 32t / 44t
CAB TYPE	**Sleeper**	Sleeper / **Day Cab**
YEARLY MILEAGE (km/year)	120.000 – 200.000	50.000 – 100.000
DAILY MILEAGE (km/day)	**400 - 800**	**200 - 500**

Baseline trucks identified for the comparison with the two demonstrator trucks.

AE6CDCD1000075			
FCP/FCS/FCO	FGC/OPT/VCO	Description	
CA	6X2P	6X2P	
CT	AS	Stralis AS	VECTO Group 9
EP	460 C11	C11 460 CV	
MT	26T	26 ton	
SU	P	pneum post	
WB	6050	6050	

BD3CD6D1000017			
FCP/FCS/FCO	FGC/OPT/VCO	Description	
CA	6X2P	6X2P	
CT	AD	Active Day	VECTO Group 9
EP	360 C9	C9 360 CV	
MT	26T	26 ton	
SU	P	pneum post	
WB	4200	4200	

Figure 31 IVG specific VPs identified as the state-of-the-art baseline diesel trucks.

The reason for this choice is twofold: first, the results are solid and benefit of high-reliability, second the LCA models that are going to be developed in WP7 will benefit from the work conducted in WP1. In fact, the two demonstrators will be designed and prototyped so that several components will be taken as carryover from the diesel configurations (e.g., front axles, suspensions, tag-axles, trailer connections) while other systems will be removed or added to the diesel configurations based on their functions. Instead, the results of the literature review serve to depict how POLITO's assumptions are localized in the existing literature and to validate the results obtained in this deliverable.

6.1 Goal and scope definition

Hereafter and in Figure 34, the main assumptions adopted in the LCA assessment have been reported.

The system boundary is cradle-to-grave (Figure 32). The environmental impacts have been evaluated considering all the emissions occurring along the full life cycle of the vehicles (i.e., 700,000 km in compliance with [84]). In terms of life cycle phases, the boundary includes the emissions of raw material acquisition and pre-processing, transport of raw materials, manufacturing, distribution, use (i.e., WTT, TTW, and maintenance), collection at EoL of the used vehicles, and EoL (Figure 32).

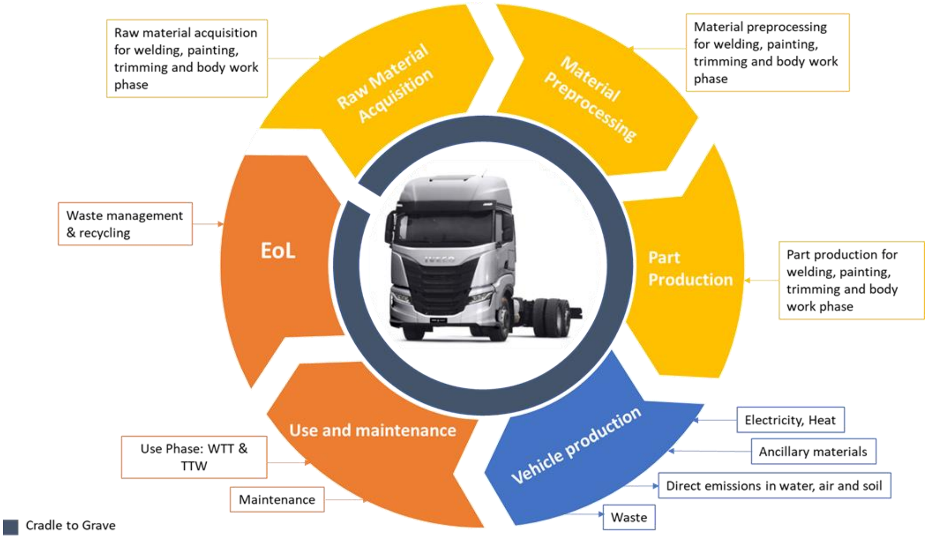


Figure 32 System boundary of the LCA study in terms of life cycle phases

In terms of components (Figure 33), the system boundary includes most of the components that are involved in the bill of materials of the vehicles under study. Currently, the vehicle models are based on primary data provided by IVG and the components included in the boundary constitute more than 80 w/w% (i.e., 84 w/w% for the long-haul truck and 83 w/w% for the regional truck). Less than 20 w/w% is currently cut-off and great efforts are in place to enhance this primary data coverage to more than 90% by the end of WP7.

For what concerns granularity (Figure 33), this study is based on the so-called vehicle's functional structure. The vehicle is disaggregated from level 0 (the vehicle as a whole) to level 4 (what Iveco refers to as "Funzione Tecnica", FT). It should be noted that the level of granularity has no bearing on the quantity of environmental effect associated with the vehicle, but it does influence the ability to plan and implement environmental strategies. In fact, the deeper is the granularity level, the greater the chance of detecting the components that cause meaningful environmental impacts. This study has a granularity able to detail the environmental results up to level 4 (Figure 33). As an example, this study evaluates not only the emissions of the vehicle as a whole, but it can also give insights in the emissions of the vehicle's subassemblies up to level 4 (e.g., internal combustion engine (ICE), rear axle, diesel oil tank, AdBlue tank).

- Set up two baseline LCA models based on comparable 2020 (Diesel) trucks
- Quality parameters for an LCA study are:
    - Ensured granularity*
    - Primary data coverage

The objective is to achieve a level 4** granularity and a primary data coverage higher than 90%.

Level 4 granularity → achieved!

Primary data coverage → **84 w/w%** long-haul

83 w/w% regional

material comp based on secondary data

*It should be noted that the level of granularity has no bearing on the quantity of environmental effect associated with the vehicle, but it does influence the ability to plan and implement environmental strategies. In fact, the deeper is the granularity level, the greater the chance of detecting the components that cause meaningful environmental impacts.

**the vehicle is disaggregated from level 0 (the vehicle as a whole) to level 4 (what Iveco refers to as "Funzione Tecnica", FT).

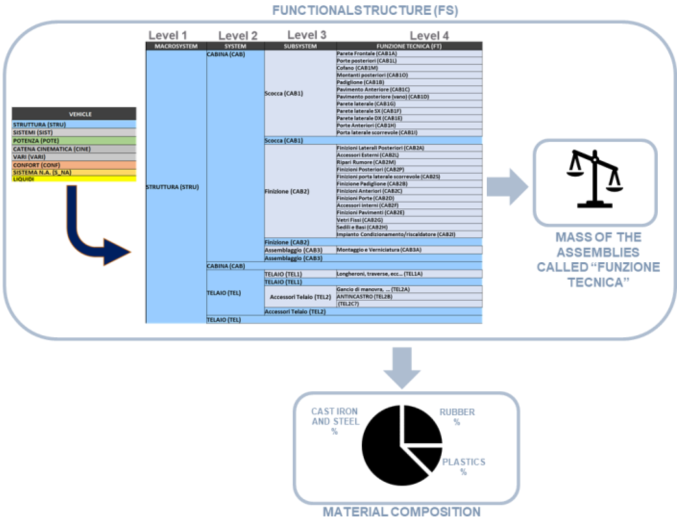


Figure 33 System boundary of the LCA study in terms of vehicle components

The system's function and functional unit are central elements of an LCA. Without them, a meaningful and valid comparison especially of products is not possible. In the sense of an LCA, function means to specify the analyzed object quantitatively and qualitatively. This is generally done by using the functional unit that names and quantifies the qualitative and quantitative aspects of the function(s) along the questions "what", "how much", "how well", and "for how long". The functional unit is 1 ton of transported goods by means of the vehicle under study along 1 km of the entire lifetime of the vehicle (Figure 34).

SimaPro v9.4 has been used as the LCA software while Ecoinvent v3.8 APOS has been used as the background database and as source of secondary data to fill the gaps (Figure 34). Literature studies and additional databases have been used to fill the gaps (e.g., EverBatt, GREET).

The assessment has been carried out by adopting the ILCD impact categories developed by the European Commission, as released in the EF 3.0 method (European Commission 2023).

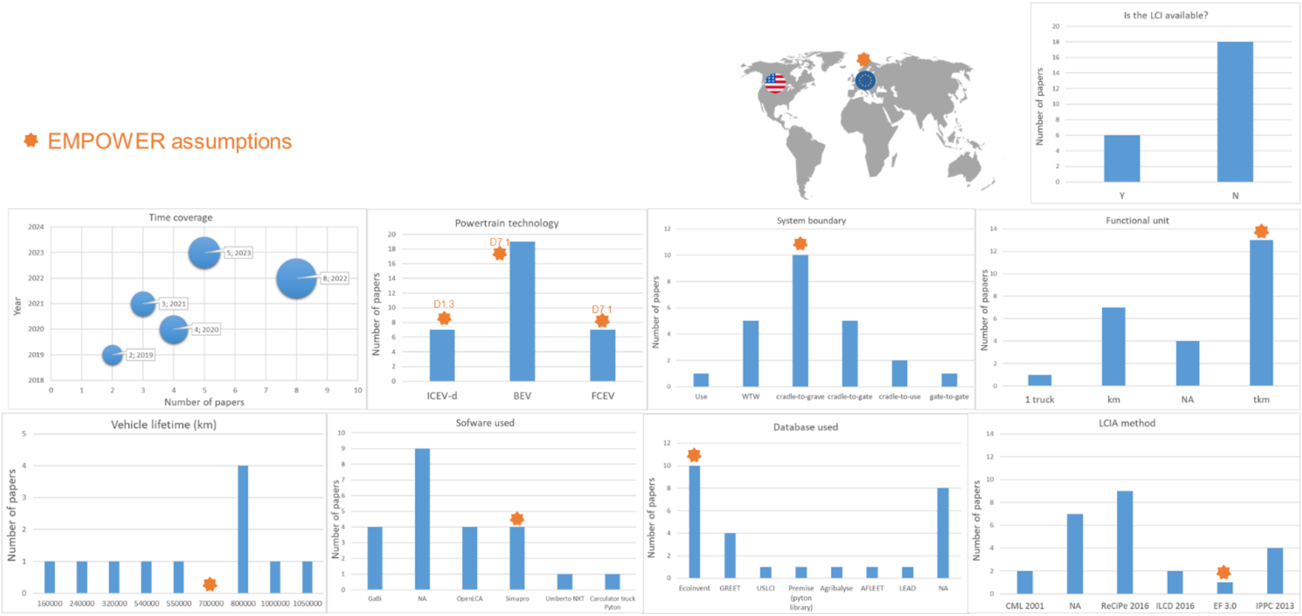


Figure 34 Summary of the main assumptions adopted in the LCA assessment.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

6.2 LCA of the two baseline diesel trucks

The main characteristics of the two baseline vehicles have been reported in Table 4. The architectures that have been chosen for the long haul and regional distributions consist of 6x2 rigid trucks (wheelbase 6050 mm and 4200 mm, respectively). For the long-haul distribution, a sleeping cabin has been foreseen, while, for the regional distribution, a day cabin has been foreseen.

The system boundary can be divided into upstream, core and downstream according to the subdivision made in the PCR of public and private buses and coaches [85]. The upstream stage includes all the energy and material flows related to the production of vehicle components and their transport to the gate of IVG plant. The core stage includes the assembly of the vehicle in IVG plant. The downstream stage includes all the stages following the departure from the IVG plant.

Therefore, the upstream processes considered in this study are as follows:

- Raw material acquisition and material processing (transport included).

Part weights are primary data provided by IVG (Paragraph 6.3) while the material composition of each part is secondary data mainly based on POLITO’s previous work on an IVG light-duty commercial vehicle and GREET to fill data gaps. POLITO and IVG are working to substitute these data with primary data by the end of WP7. This will be beneficial for the LCA of both the baselines and EMPOWER demonstrators. Lastly, the transportation of raw materials to a European plant as well as the processing of materials, assuming average European manufacturing processes, were included.

The core processes considered are as follows:

- Consumption of energy in the IVG plant.
- Consumption of ancillary materials in the IVG plant.
- Consumption of water in the IVG plant.
- Management of waste in the IVG plant.

The excluded core processes are as follows:

- Direct emissions in water, air, soil in the IVG plant.

The downstream processes considered are as follows:

- Transport of the vehicle to the consumer.
- Vehicle use (WTW), including Well-to-Tank (WTT), Tank-to-Wheel (TTW) and maintenance stages.

TTW emissions are currently based on primary data for fuel consumption and carbon dioxide emissions, while emissions factors have been used for pollutant emissions and non-exhaust emissions. POLITO and IVG are working to try including at least pollutant emissions as primary data by the end of WP7.

- EoL of the vehicle.

The excluded processes are as follows:

- Production/assembly of parts.

Emissions occurring during the production of all those parts that are not produced in IVG plant are disregarded, because there are no available primary or secondary data. According to the PCR of public and private buses and coaches [85], only data referring to processes and activities upstream in a supply chain over which an organization has direct management control shall be specific and collected on site, while data referring to contractors that supply main parts or main auxiliaries could be requested from the contractor as specific data or calculated using general or proxy data from the recommended databases. Nevertheless,

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

according to [40], besides the issue of the limited access to data, the environmental significance of part production is low (<1% of production phase).

- Transport of parts from tier 1 suppliers to IVG plant.

Currently we base the info related to supplier distances on POLITO's previous work on an IVG light-duty commercial vehicle, assuming these values as average for a vehicle manufacturer in Europe. POLITO and IVG are working to collect all the supplier locations and add this impact by the end of WP7. However, this lack does not harm the results of this deliverable because, according to POLITO's previous work and experience, this part accounts for 0.1% of the overall life cycle GWP in diesel light-duty commercial vehicles.

Table 4 Main characteristics of the baseline vehicles under study

Model	VP 1 - LONG HAUL - AE6CDCD1000075	VP 2 - REGIONAL- BD3CD6D1000017
Axis configuration	6x2P	6x2P
Cab type	Sleeper (AS)	Active day (AD)
Wheelbase	6050	4200
Gearbox type	TX-12M	TX-12M
Suspension	Pneumatic rear	Pneumatic rear
Gross vehicle weight[1]	26 ton	26 ton
VECTO vehicle curb weight[2]	8717 kg	7528 kg
Engine	Cursor C11	Cursor C9
Engine power	460 CV	360 CV
Euro class	Euro 6	Euro 6
Production site	Madrid (Spain)	Madrid (Spain)

[1] Maximum vehicle weight comprised of payload without trailer

[2] Curb vehicle weight as in VECTO simulations provided by IVG.

6.3 Data collection and management

All the collected data and data sources are summarized in the scheme of the data collection management shown in Figure *35*. First, to ensure granularity, the functional structure has been derived from the IVG Product Development Cost Management (PDCM) system. The Functional Structure groups all the vehicle parts according to five levels of aggregation, starting from the vehicle itself (level 0) and arriving to “Funzione Tecnica” (level 4). Second, IVG has provided the bill of materials (BoM) of the baseline vehicles under study (spreadsheet extractions from Matrix and WVTA). Then, IVG has processed the weight information of BoM parts by means of a rollup algorithm and aggregated them in all the functional structure levels, up to the entire vehicle. At this point, POLITO created the LCA model in SimaPro filling data gaps with secondary data.

For the preliminary assessment of EMPOWER demonstrators, POLITO has created the LCA models of hydrogen, FC system, Li-ion battery, and hydrogen tanks. The main characteristics of the two EMPOWER demonstrators have been reported in Table 5. The BEV demonstrator has the same overall dimensions as the ICE-propelled version. Therefore, the functional structures of the EMPOWER demonstrators have been created considering certain parts as carry-over from traditional diesel configurations, removing those parts that are limited to diesel vehicles (e.g., ICE, diesel tank, Adblue tank, etc.) and adding new parts (e.g., FC system, Li-ion battery, hydrogen tanks, integrated e-axle). A preliminary assessment of fuel and energy consumption of the EMPOWER demonstrators has been provided by AIT to model the use phase.

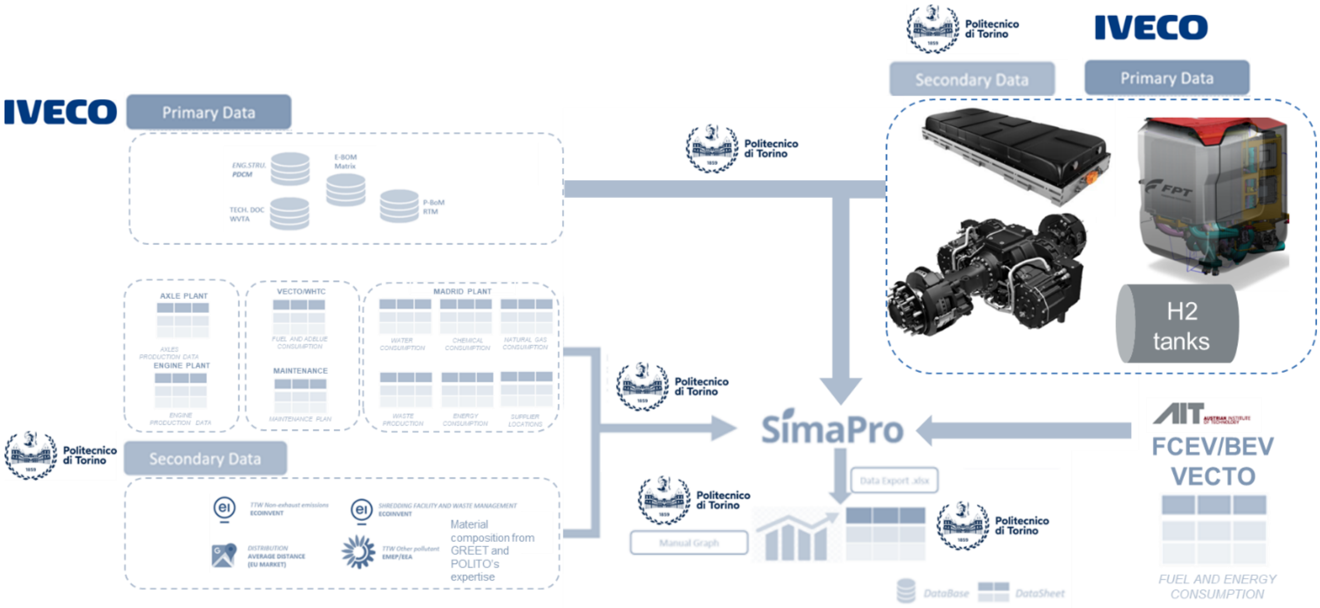


Figure *35* Scheme of the data collection management

Table 5 Main characteristics of the EMPOWER demonstrators under study.

Diesel model used as baseline	VP 1 - LONG HAUL - AE6CDCD1000075	VP 2 - REGIONAL- BD3CD6D1000017
Axis configuration	6x2P	6x2P
Cab type	Sleeper (AS)	Active day (AD)
Integrated e-axle	dual e-drives e-axle	dual e-drives e-axle

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Integrated e-axle weight	1390 kg	1390 kg
Motor power	240 kW	240 kW
Vehicle production site/s	Madrid (Spain) + Ulm (Germany)	Madrid (Spain) + Ulm (Germany)
Estimated vehicle (empty) weight[1]	10514 kg	10107 kg

[1] Estimated using the curb weights of the diesel baselines as starting point (Table 4), removing those parts that are related to the diesel powertrain (e.g., fuel tanks, engine, gearbox) and adding those parts that are new in the two demonstrators (e.g., integrated axle, batteries, fuel cell system, hydrogen tanks). The vehicle is considered empty, without fuel and liquids.

6.4 Manufacturing

The manufacturing step is the core part of this LCA study because the management of the plant is direct responsibility of IVG.

The manufacturing of the vehicle begins in the welding shop (Valladolid), where the components (i.e., metal sheet) of the body are assembled. First, lateral panels and floors are welded together, and the doors and hood are installed to form the body of the vehicle. The welding phase is all mechanized and performed by robots. After the quality controls, the body enters the painting shop, otherwise it is sent to recovery. In the painting shop, the body is washed and then undergoes a cataphoresis treatment. This process involves the electro-deposition of paint by means of immersion under a continuous electrical current. The deposited film is acrylic or epossidic resin, and it confers an elevated anticorrosive property to the body. This process ends with the drying of the body at a high temperature (150 °C – 180 °C). The body is then sealed with polyurethane sealants and painted by robots. Once it’s ready, the cabin base is sent to Madrid to continue the process.

The next phase is called trimming phase and consists of the assembly of parts, starting from the roof and continuous with the dashboard and seats, that are installed on the frame of the vehicle. This phase also includes phase also includes the assembly of other parts like windshield, mirrors, headlights. The framework phase, in which the chassis, powertrain, driveline and after-treatment system are assembled and then combined with the frame from the trimming phase, takes place at the same time. After all these operations, the vehicle is complete and is sent to the testing area, where the alignment and the hydraulic tests are performed. After the functional tests, the vehicle is finished, sold and transported to the consumer.

The life cycle inventory of vehicle manufacturing includes all the input flows occurring in the plant: energy, ancillary materials, water, and waste. Also, the plant has an internal production of electricity by means of solar panels. This green electricity rate has been taken into account in this study. The plant does not produce the vehicles under study only, but also other vehicle types, therefore an allocation of the emissions was necessary. In this deliverable, the allocation is based on the number of vehicles produced in the reference years, nevertheless, the intention is to evaluate the effect of a different allocation method during WP7.

6.5 Use

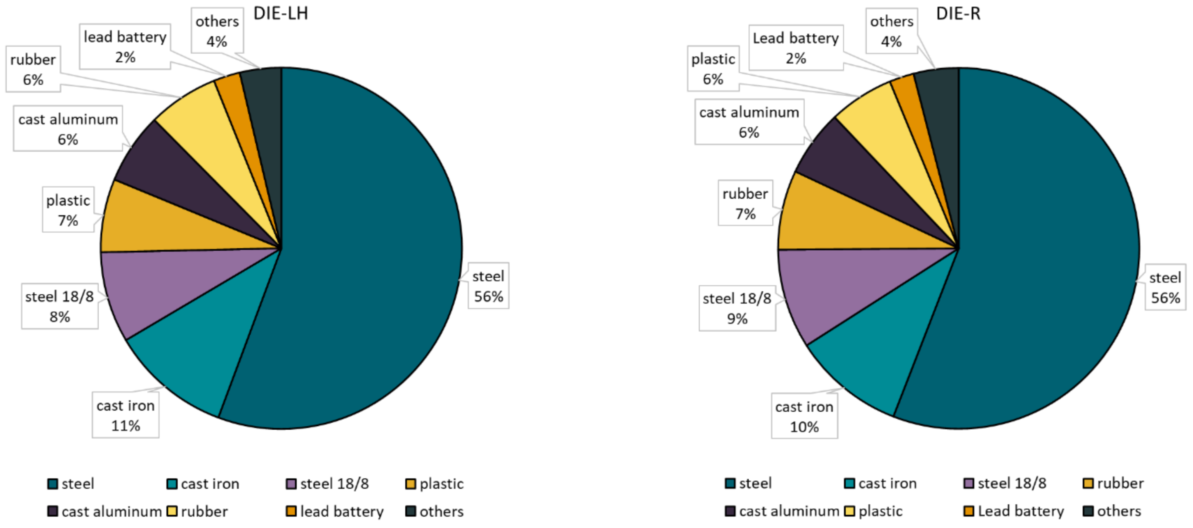
For the fuel consumption and CO_2 emissions of the two baseline vehicles, primary data have been provided by IVG based on the vehicle’s homologation data. Instead, emissions factors taken from the literature and available Ecoinvent background datasets have been used for pollutant emissions (i.e., carbon monoxide, dinitrogen monoxide, ammonia, non-methane volatile organic compounds, nitrogen oxides, particulates <2.5

um, lead, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene) for diesel configurations, and non-exhaust emissions (i.e., brake, road, and tire wear emissions) for all configurations.

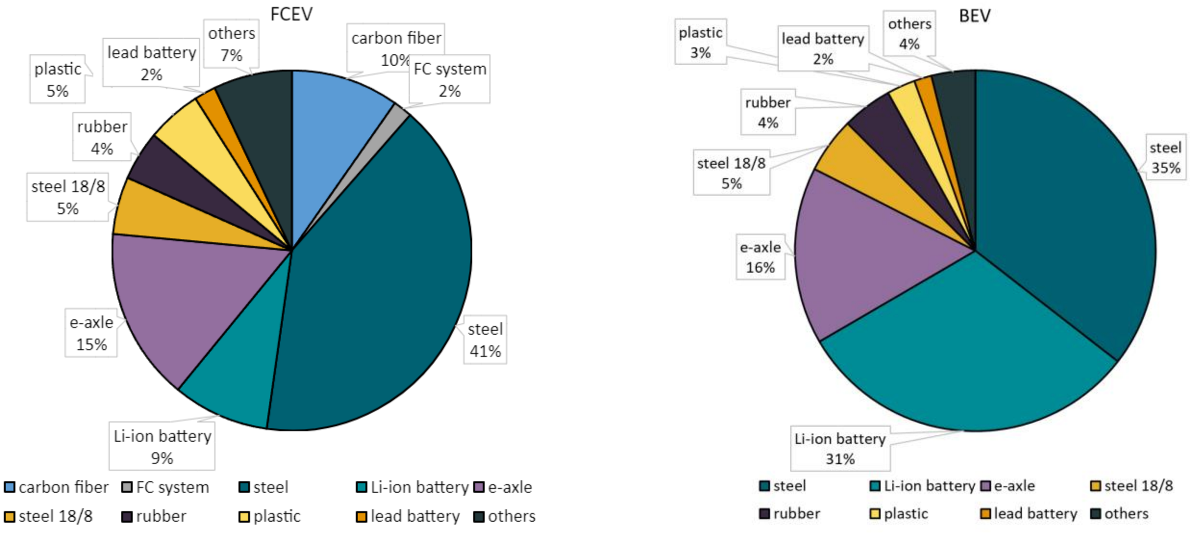
For the EMPOWER FCEV, the fuel consumption of the present study has been estimated through a simulation model of the FCEV, considering a VECTO long-haul driving cycle with elevation, resulting in 0.0845 kg H_2/km. In the FCEV, the SOC of the battery is balanced, therefore there is no influence on energy consumption. For the EMPOWER BEV, the fuel consumption of the present study has been estimated through a simulation model of the BEV, considering a VECTO regional driving cycle with elevation, resulting in 1.778 kWh/km. For both simulations, the overall vehicle consumption of the auxiliaries is used as a constant value of 1 kW, and the HVAC is not included.

6.6 End-of-Life

EoL modelling has been broadly discussed methodologically within the LCA community in recent years, but there is no consensus on the single best approach [41]. Among the two most used EoL approaches, the one used in this study is the “Avoided-burden approach” sometimes referred to as “0:100 approach”. To model the EoL phase, first the four vehicles have been studied in terms of material composition. The material compositions of the four vehicles under study are shown in Figure 36.



(a) (b)



(c) (d)

Figure 36 Material composition of the four vehicles under study: a) DIE-LH; b) DIE-R; c) FCEV; d) BEV

The LCA model of the EoL phase of the Li-ion battery is reported in a dedicated paragraph (Paragraph 6.8.1) as well as the LCA model of the EoL phase of the FC system (Paragraph 6.7.2). Instead, the LCA model of the EoL phase of the four vehicles is based on the following assumptions. Fluids (e.g., lubricating oil, refrigerants) are assumed to be collected during the depollution step of the waste management process, as well as batteries. Cast aluminum, magnesium alloys, copper, steel, lead battery, control unit and easily dismantlable electric components (fridge) are assumed to be collected and recycled with the collection rates and efficiency rates reported in Table 6. Other materials/components like glass and plastics, are assumed to be partially incinerated and partially disposed to landfill. The assumed Ecoinvent background datasets are documented in Table 6.

Table 6 Main assumptions for the LCA model of the EoL phase of the four vehicles under study.

Material/component	**Recovered? (Y/N)**	**Collection rate (%)**	**Recycling efficiency (%)**	**Ecoinvent datasets**
adhesive	N	-	-	
cast aluminum	Y	90	93	AVOIDED: Aluminium, cast alloy {GLO} WASTE TREATMENT: Aluminium scrap, post-consumer {GLO}| market for | APOS, U Aluminium scrap, post-consumer, prepared for melting {GLO}| market for | APOS, U"
cast iron	N	-	-	
control unit	Y	100	(*)	(*)
copper	Y	67	63	AVOIDED: Copper, anode {GLO}| market for copper, anode | APOS, U WASTE TREATMENT:

				Copper scrap, sorted, pressed {GLO}| market for | APOS, U Copper, cathode {SE}| treatment of metal part of electronics scrap, in copper, anode, by electrolytic refining | APOS, U
fridge	Y	100	(*)	(*)
glass	Y	100	0	WASTE TREATMENT: Waste glass {Europe without Switzerland}| market group for waste glass | APOS, U
lubricating oil	Y	100	0	
Magnesium alloys	Y	90	93	AVOIDED: Aluminium, cast alloy {GLO} WASTE TREATMENT: Aluminium scrap, post-consumer {GLO}| market for | APOS, U Aluminium scrap, post-consumer, prepared for melting {GLO}| market for | APOS, U"
organic	N	-	-	
paint	N	-	-	
plastic	Y	100	0	WASTE TREATMENT: Waste plastic, mixture {RER}| market group for waste plastic, mixture | APOS, U
platinum	N	-	-	
polyester, unsaturated	N	-	-	
polyurethane	N	-	-	
refrigerant	Y	100	0	
rubber	N	-	-	
steel	Y	926	88	AVOIDED: Pig iron {RER}| market for pig iron | APOS, U WASTE TREATMENT: Steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | APOS, U
steel 18/8	Y	926	88	AVOIDED: Pig iron {RER}| market for pig iron | APOS, U WASTE TREATMENT: Steel, low-alloyed {Europe without Switzerland and Austria}| steel production, electric, low-alloyed | APOS, U
textiles	N	-	-	
wrought aluminum	N	-	-	

zinc	N	-	-	
Lead battery	Y	100	98.8	AVOIDED: Lead {GLO}| market for | APOS, U WASTE TREATMENT: Lead {RER}| treatment of scrap acid battery, remelting | APOS, U

*Electronics is assumed to be composed of 19% plastic, 27% aluminum, 13% copper, and 41% steel.

6.7 Preliminary assessment of the EMPOWER FCEV demonstrator

For the preliminary assessment of the FCEV demonstrator, four scenarios have been set up based on diverse hydrogen production routes namely:

- FCEV-SMR.
- FCEV-SMR+CCS.
- FCEV-AE fossil-based.
- FCEV-AE wind based.

In the long-haul distribution, it has been assumed that the FCEV has been equipped with 1 FC system, 5 hydrogen tanks, and 2 Li-ion batteries in compliance with deliverable D1.1.

For the batteries, in the FCEV, they are required for fast provision of electric power in transient driving conditions when the power increase by the fuel cell system is not fast enough. They also serve as a buffer of energy balancing the power requirements. In downhill conditions the e-axle can serve as an electric generator, charging the batteries. Hence the overall net consumption of energy will be partially recuperated and stored in the batteries. Additional scenarios are under consideration for WP7 because, according to deliverable D1.1, the final products can rely on multiple battery package choices, depending on the customer's mission (i.e., the package range moves from two, for the FCEV version, to seven batteries, for the BEV configuration, and it could potentially go up until ten batteries).

Also, 2 FC systems will allow for outstanding efficiency level, unseen power availability at the expense of increased weight and cost (deliverable D1.1). Additional scenarios are under consideration for WP7.

For the hydrogen tank, instead, 5 tanks with a total weight of 73 kg H_2 have been included in the FCEV demonstrator in compliance with deliverable D1.1. The tanks weigh 1358 kg and have been assumed to be mainly made of carbon fiber (Table 7) based on [86]. The total electricity required by the process has been taken into account, assuming a total load of 261 kWh (Table 7) based on [86].

Table 7 LCI for the LCA model of the hydrogen tanks.

Carbon fiber	871 kg
Polyurethane	56.1 kg
Glass fiber	95.2 kg
Wrought aluminum	97.8 kg
18/8 steel pipe	119 kg
plastic	119 kg
Electricity	261 kWh

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Hereafter, the main assumptions adopted for hydrogen production (Paragraph 6.7.1) and FC system have been reported (Paragraph 6.7.2).

6.7.1 Hydrogen production

This section gives an insight into the sub-task related to the assessment of the environmental impacts of hydrogen production. This sub-task aims to perform the LCA of gaseous hydrogen to feed the EMPOWER long-haul heavy-duty truck characterized by the possibility of operation at 350 and 700 bar (deliverable D1.1). As methodology guidelines, this paragraph refers to the ISO standards 14040 and 14044 [87], [88] as well as more specific guidance for performing LCAs of hydrogen technologies [89].

Four hydrogen production routes have been investigated, namely Steam Methane Reforming (SMR), steam methane reforming coupled with Carbon Capture and Storage (SMR+CCS), Alkaline Electrolysis (AE) with fossil-based electricity mix, and AE with wind-based electricity mix. The former is based on the current EU electricity mix while the latter is based on a potential green electricity mix composed of more than 96% of offshore wind electricity. SMR has been chosen because it is the current most used production method in Europe while AE with wind-based electricity has been chosen as an optimistic scenario representative of future promising technology in terms of decarbonization potential. SMR + CCS has been chosen because the combination of hydrogen production and CO_2 capture strategies may be a promising strategy.

For modeling the hydrogen production, a cradle-to-gate boundary has been assumed (Figure 37) comprising feedstock acquisition and transport, electricity production and distribution, conditioning (e.g., sulfur removal, feedstock compression, and heating), conversion (e.g., reforming, gasification, electrolysis), purification (e.g., through pressure swing adsorption (PSA), membrane purifiers), conditioning (e.g., compression, liquefaction, odorization), transport and compression at refueling station (i.e., hydrogen has been assumed to be distributed in gaseous form by means of tube trailers and it has been assumed to be compressed to 800 bar at the refueling station). For SMR this study refers to [22] but the EU electricity mix has been assumed for electricity production adopting the inventory data available in Ecoinvent database. For SMR + CCS, this study refers to [90] but the EU electricity mix has been assumed for electricity production adopting the inventory data available in Ecoinvent database. Contrarily to [23], natural gas has been assumed to be supplied through pipelines adopting the EU geography available on Ecoinvent database. For AE this study refers to [91] but assuming different electricity mix based on the set up scenarios (i.e., fossil and wind-based). The different electricity mixes have been incorporated at that point of the life cycle in which grid electricity is supplied to operate the electrolyzer.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

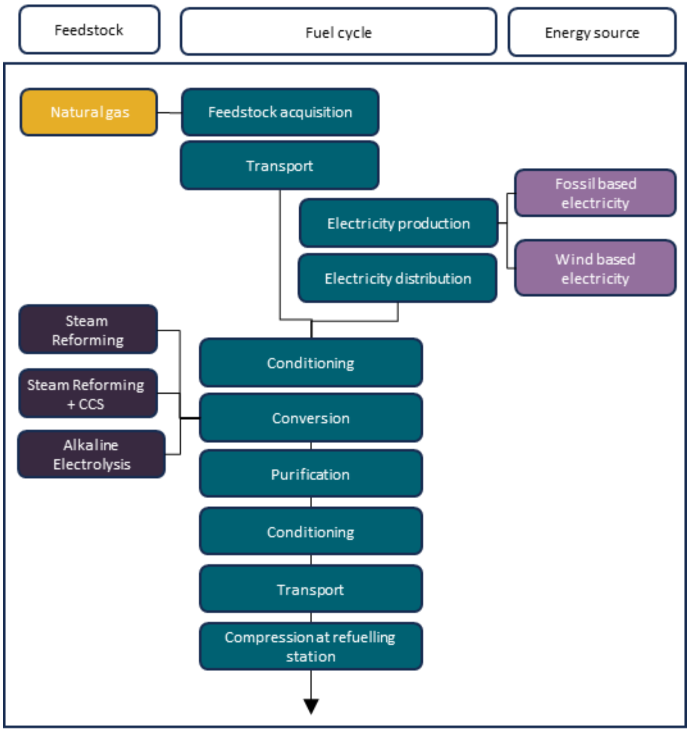


Figure 37 System boundary of the hydrogen production routes.

6.7.2 Fuel cell system

This section gives an insight into the sub-task related to the assessment of the environmental impacts of the Fuel Cell (FC) system. This sub-task aims to perform the LCA of an FC system suitable for the EMPOWER long-haul heavy-duty truck characterized by a mass of 40 tons, a driving range of 750 km, and a lifetime of 700,000 km. The identified targets for fuel cells are pointing to have a 150 kW to 200 kW system, with unprecedented efficiencies, above 50 % also in the least efficient points (deliverable D1.1). 1X system configuration will allow very good efficiency levels and enough power to cover mountain mission demands while having a moderate impact on vehicle weight and overall system cost (deliverable D1.1). As methodology guidelines, this paragraph refers to the ISO standards 14040 and 14044 [87], [88] as well as more specific guidance for performing LCAs of fuel cells [89]. POLITO has developed the LCA model of the FC system based on literature but with a focus on the EMPOWER requirements set so far. The model is representative of the entire life cycle of the FC system, containing Proton Exchange Membrane Fuel Cells (PEMFCs). The main assumptions adopted for the LCA of the FC system are summarized in Table 8.

Table 8 Main assumptions adopted for the LCA of the FC system

Assumptions		
Fuel cell type	PEM	
FC system net power	200 kW	Based on deliverable D1.1
FC production site	Average GLO	
FC system production site	EU	
FC system EoL	EU	
Fuel consumption (kg H_2/km)	0.0845	Preliminary assessment based on partner input, to be fine-tuned in WP7
FC replacement	No	

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

For the material composition of the FC system, this study is based on secondary data and refers to [86]. The material composition has been reported in Table 9.

Table 9 Material composition of the FC system

Membrane	Tetrafluoroethylene (TFE): 96% Sulfuric acid: 4%
GDL	Carbon fiber reinforced plastic: 74% TFE:11% Carbon black:14% Solvent:1%
Catalyst	Pt loading:0,4 mg/cm^2 Platinum:10% Carbon black: 3% TFE: 0,4% Solvent:86,6%
Bipolar plates	Graphite: 69% phenolic resin: 29%
Gasket	Polysulfide
End of plates, collectors	Glass fiber: 50% Epoxy resin: 50%

6.8 Preliminary assessment of the EMPOWER BEV demonstrator

For the preliminary assessment of the BEV demonstrator, two electricity mixes, namely fossil-based and wind-based, have been compared. Therefore, two scenarios have been set up, namely “BEV” and “BEV wind”. The fossil-based electricity mix is the EU mix. In the regional distribution, it has been assumed that the BEV has been equipped with 7 batteries in compliance with deliverable D1.1. Additional scenarios are under consideration for WP7 because, according to deliverable D1.1, the final products can rely on multiple package choices, depending on the customer’s mission (i.e., the package range moves from two, for the FCEV version, to seven batteries, for the BEV configuration, and it could potentially go up until ten batteries).

6.8.1 Li-ion battery pack

POLITO has developed the LCA model of the Li-ion battery pack based on a literature review and secondary data sources. Certain primary data have been gathered from FPT, namely the cathode chemistry (NMC532), the battery pack mass (389 kg), and the battery pack capacity (68 kWh). The number of battery packs considered in the BEV and FCEV are based on deliverable D1.1 and will be fine-tuned once the final prototypes are developed at the end of the project and assessed in terms of LCA in WP7. The model is representative of the entire life cycle of the battery pack, containing prismatic cells (Table 10). The assumed material composition of the cells and battery packs is reported in Table 11. The EoL has been modeled as an ad-hoc combined pyrometallurgical-hydrometallurgical process. Recovered materials are copper, lithium carbonate, nickel, cobalt, and manganese. The recycling efficiencies are 95%, 80%, 98%, 98%, and 98%, respectively.

Table 10 Main assumptions adopted for the LCA of the Li-ion battery pack.

Assumptions		
Cathode chemistry	NMC532	FPT Dataset
Battery pack mass	389 kg	FPT Dataset
Battery pack capacity	68 kWh	FPT Dataset

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

N. Battery packs BEV	7	Based on deliverable D1.1
N. Battery packs FCEV	2	Based on deliverable D1.1
Cell production site	USA	
Battery production site	Italy	
Battery pack recycling site	EU	
Battery pack recycling technology	Pyro+hydro	
Battery replacement	No	

Table 11 Material composition of the Li-ion battery pack

Cell energy (kWh)	0.250
Cell mass (kg)	0.808
Cell materials (kg/kgcell)	
Active cathode material	0,52
Graphite	0,31
Carbon black	0,01
Binder (PVDF)	0,01
Copper	0,10
Aluminum	0,06
Electrolyte: $LiPF_6$	0,02
Electrolyte: EC	0,06
Electrolyte: DMC	0,05
Plastic: PP	0,01
Plastic: PE	0,002
Plastic: PET	0,003
NMP	0,17
Binder anode	0,01
Pack materials (kg/kgbatterypack)	
Copper	4,1
Aluminum	35,4
Plastic: PP	0,4
Insulation	2,1
Electronic part	3,7
Steel	85,5
Iron	16,0
Coolant	11,5

7. TCO model

The TCO model has been developed through the joint effort of the Polytechnic of Turin and IFP Energies Nouvelles. The TCO of the two baselines also for the preliminary evaluation of the two new technologies are evaluated for the full life cycle of the vehicle. that is the minimum life requirement for the vehicle class according to the Euro7 draft. The TCO model focuses on the fixed and variable costs that a fleet operator must deal with during the full lifecycle. These include the purchase cost. all the taxes related to the ownership and operation. the Driver Cost that differs from country to country, the maintenance and repair costs. the payload loss cost, the time penalty cost, the energy carrier cost and lastly the truck depreciation. Furthermore, since the TCO is very geographically dependent. it is decided to include. besides the average European value costs. the costs linked to the country considering seven countries that represent more than three-quarters of the heavy goods vehicle market. Therefore. a geographical analysis was made of seven countries: France, Germany, Italy, Netherlands, Poland, Spain, United Kingdom which is no longer a European Union member but is included in the analysis.

The TCO model is built to best compare the two baselines with the two demonstrators that will be developed throughout the project. therefore, is done for diesel. battery-electric and fuel-cell electric heavy-duty vehicles. The baseline vehicles. the diesel-powered ones. are two trucks representative of the year 2020 according to the project proposal. The goal is to achieve the TCO parity in 2030 for the two demonstrators with the two baselines. Furthermore, at the end of the project, it will be necessary to assess also the two new technologies (BEV and FCEV) in 2050 aiming for a reduction of the TCO cost compared to the conventional baseline. The main output of the analysis is the TCO calculated as the net present value (NPV) of all costs incurred.

Although the inflation rate is seldom considered in the TCO studies, it has been decided to account for the rise in prices to better reflect real-world conditions.

Regarding the discount rate, the study will adopt a rate of 10%. This decision is based on the observation that most studies in the literature use a discount rate between 7% to 10%. Specifically, a rate of 10% was chosen because the transition to zero-emission freight transport presents a significant challenge for fleet operators, and thus, a higher opportunity cost is expected due to the increased risk.

The TCO analysis is focused. as introduced before. from the fleet operator point of view which is owning the truck throughout the full life cycle. The analysis includes all the taxes linked to the ownership and operation of the truck. It used a discount rate of 10% to assess the NPV of the operation cost that occurred year by year during the period under analysis. The main parameters are shown and summarized in the table. It is worth noting that none of the external cost [92] is included in the TCO.

Table 12-Main TCO assumptions

Parameter	Fleet operator perspective
Analysis period	700000 km driven
Discount rate	10%
Inflation	Average inflation over the last twenty years in Europe
Taxes	All taxes linked to ownership and operation
Road tolls	Included
External costs	Excluded

The trucks energy consumption of the diesel-powered trucks was taken from the VECTO certification results of the two baselines. as shown in Table 13. The preliminary assessment of the energy consumption of the Battery-electric and Fuel-electric vehicles was simulated by AIT. Surely. this value of energy consumption will be updated throughout the project development and the results will be included in the deliverable belonging to the WP7.

Table 13-Energy Consumption (kWh/km)

	RD-Diesel	LH-Diesel	RD-BET	LH-FCET

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Energy consumption (kWh/km)	2.44	3.23	1.78	2.81

7.1.1 Fixed Costs

This section figures all the parameters of the TCO model that are not dependent on the distance traveled by truck analysed. These costs include only the vehicle purchase cost concerning the acquisition cost (no interests on loans are considered). registration and ownership taxes. insurances.

Purchase Cost

Based on the literature review. it has been demonstrated that the purchase price value for a comparable diesel truck with the two demonstrators of the project cannot be extracted from the literature. Therefore. IVECO provides the purchase cost of the two-baseline diesel trucks. therefore, the purchase cost is the primary data. About the preliminary assessment of the two new technologies demonstrators. the purchase cost is not yet available. since the project is ongoing. Therefore, an estimation method has been developed to preliminarily evaluate the purchase cost of the ZE-Truck if this value is not available. The method can be described as follows:

First. it is important to identify the Internal Combustion engine correspondent configuration. with all the technical aspects. Secondly. the model will remove all the subsystems that are not in the ZE-Truck (e.g., Conventional Powertrain. Conventional Driveline. Aftertreatment subsystem. etc.). Lastly. the model will add all the subsystems that are needed in a ZE-Truck. modeling them with the technical parameters acquired from the D1.1. with the specific prices taken from the literature together with integration factors that serve to scale the single component cost to the vehicle integration. The workflow procedure of the estimation method is highlighted in Figure 38.

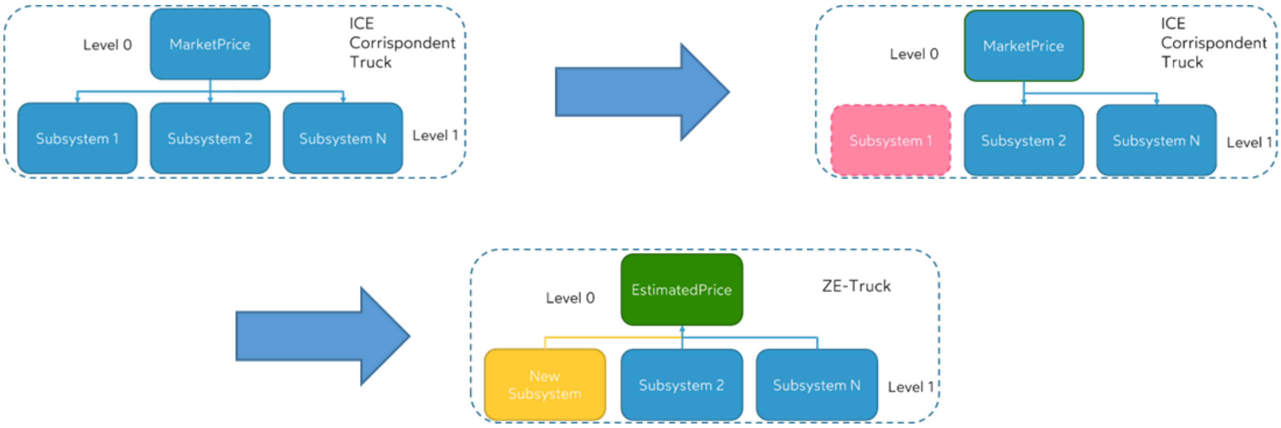


Figure 38-Purchase Cost Estimation

Taxes

The transport taxes. specifically, the Registration and Ownership taxes. were obtained from the European Commission report [93] and were verified with the fleet operator partner of the project, Guber Logistics. The data regarding insurance was sourced from the report published by Comité National Routier [94] and was adjusted with the assistance of Gruber Logistics to account for changes that have occurred over the years. The collected data is presented in Table 14.

The Registration tax is a one-time tax that a fleet operator must pay when purchasing a truck. Therefore. it has already been actualized and there is no need to apply the NPV formula. The Ownership tax. on the other hand. is a fixed cost in terms of monetary value that occurs annually during the truck ownership period. This necessitates the actualization of the cash flow created from the tax. and thus, the use of the net present value formula to discount it and make the cash flow at year 0 considering the value of time in monetary consideration. Similarly. the insurance is a yearly "tax" that is mandatory to operate a truck. Therefore. the cash flow created by the insurance tax is actualized with the NPV formula to year 0.

Table 14-Taxes

Country	Registration	Ownership (EURO/y)	Insurance (EURO/y)
Germany	0	929	3000
Spain	0	850	3000
France	800	950	3000
Italy	1500	1000	3000
Netherlands	0	1375	3000
Poland	290	1300	3000
United Kingdom	0	550	3000
Average EU	370	993	3000

7.1.2 Variable Costs

Variable costs are costs that vary with the distance traveled by the vehicle. In the transport of goods sector, these costs include driver costs. maintenance cost, road use cost, and energy carrier cost. These costs are a function of the operation. which means they depend on the number of kilometers driven by the truck in a year.

Driver cost is the cost of hiring a driver to operate the vehicle. This cost includes the driver's salary. benefits. and other expenses related to the driver's employment.

Maintenance cost is the cost of maintaining the vehicle. This cost includes the cost of parts. labor. and other expenses related to the maintenance of the vehicle.

Energy carrier cost is the cost of the fuel or energy used to power the vehicle. This cost includes the cost of the fuel or energy itself. as well as any other expenses related to the use of the fuel or energy.

These costs are all a function of the number of kilometers driven by the truck in a year. As the number of kilometers driven increases. so do the variable costs associated with the operation of the vehicle.

Highways Tolls

European countries have implemented road-use taxes based on the distance driven by the vehicle in kilometers and the number of axles. The United Kingdom is the only country that currently does not impose a kilometer-based road charge. Among the countries. the lowest road tolls are found in Poland with 5.5 EURO cent/km. while the highest is in France with 32 EURO cent/km. It should also be noted that there are different approaches for collecting road charges among European countries. In some countries. such as France. Italy. and Spain. the road tolls are given to concession consortiums. with agreements that typically run for decades. In other countries. such as Germany. it is through a network-wide tolling system. Poland has a mix of concessions and distance-based road tolling. Table 15 summarizes the highway tolls considered taken from [80]. It should be noted that all tolls are representative of the year 2020. For instance. Germany made important changes in highway tolls in the last year leading to almost double the 2020 highway tolls for conventional vehicles. It is important to note that in Germany the Zero Emissions Vehicles do not pay highways tolls. yet.

Table 15-Highways Tolls

Country	Highways Tolls (EURO/km) 2020
Germany	0.187
Spain	0.16
France	0.32
Italy	0.19
Netherlands	0.15
Poland	0.055
United Kingdom	0
Average EU	0.152

Driver Cost

This paragraph delineates the heterogeneous nature of driver costs across European countries. emphasizing a meticulous breakdown into three primary constituents: average salary. travel allowances. and employer's social contribution. Each distinct cost parameter is meticulously documented on a country-specific basis. drawing from the most recent reports concerning the employment and remuneration conditions of international lorry drivers in Europe. These reports. published by the Comité National Routier within the past three years. serve as the primary source of data.

The analysis underscores a discernible disparity in hourly driver costs among the selected countries. France emerges as the country with the highest driver cost per hour. amounting to 36.01 EURO/h. In stark contrast. Poland exhibits the lowest driver cost per hour. standing at 11.19 EURO/h. To encapsulate the comprehensive findings. Table 16 succinctly presents a summary of the driver costs in the seven countries considered in this study.

Table 16-Driver Cost

Country	Average salary	Travel allowances	Employers' social contribution	Driver Cost (Euro/y)	Yearly driving time (h)	Driver Cost (Euro/h)	Reference
United Kingdom	35400	7700	3519	46619	1895	24.60	[95]
Netherlands	37106	6668	23798	67573	1938	34.87	[96]
Poland	6636	15480	1459	23575	1980	11.91	[97]
Spain	19481	14954	7130	41565	1980	20.99	[98]
Germany	33360	6780	6699	46839	1735	27.00	[99]
Italy	31192	14600	11454	57246	1860	30.78	[100]
France	34992	11008	9448	55448	1540	36.01	[101]
Average EU	28309	11027	9072	48409	1847	26.59	

Maintenance Cost

The maintenance costs of a vehicle are a crucial factor in determining its overall cost of ownership. The maintenance cost typology has been modeled based on primary data provided by IVECO. which has been grouped into four categories: lubricants. oil. AdBlue refilling. repair and preventive maintenance. and tires. The preliminary estimation of the maintenance costs related to the two new technologies trucks is based on data from ICCT reports. which shows that battery electric trucks (BET) and fuel cell electric trucks (FCET) can obtain a reduction compared to diesel-powered trucks. This is because there is no need to refill AdBlue and lubricant oils. and because a conference paper and several reports have reported that the repair and maintenance of BET can be 30% lower than the counterpart. However. the FCET could reach a reduction only in the future because nowadays the costs related to the maintenance of the tank are high and therefore there is a parity at the state of the art if we consider a 2020 baseline. In 2030. a reduction of up to 25% compared to diesel-powered trucks could be found [102]. Table 8 shows the breakdown of maintenance costs for each truck type.

Table 17-Breakdown of maintenance cost for each truck type

Item	Diesel truck	Battery-electric truck	Fuel-Cell-electric truck	Fuel-Cell-electric truck 2030
	Cost in EURO/100km			
Lubricants. oils	0.75	/	/	/
AdBlue refilling	0.55	/	/	/
Repair and preventive maintenance	12	8.3	13.3	9.96
Tires	2.47	2.47	2.47	2.47
Total	15.77	11.04	15.77	12.43

Energy Carrier Cost

The salient importance of energy carrier costs. often surpassing 30% of the TCO for trucks. underscores its pivotal role in this study. To ensure accuracy. reliance is placed on the weekly oil bulletin published by the European Commission [103]. This bulletin furnishes real-time data on a country-by-country basis concerning Automotive Gas Oil (Diesel). encompassing all applicable taxes. Additionally. consideration is given to the partial refund of excises in countries where such reimbursement is applicable. The data extracted for this study are the average value for 2020. Table 9 summarizes all the costs country by country.

Table 18-Automotive Gas Oil Prices

Country	Price with taxes (EURO/L)	Price without taxes (EURO/L)	Excises refund (Euro/L)
Germany	1.11	0.47	0
France	1.26	0.44	0.157
Italy	1.32	0.46	0.214
United Kingdom	1.35	0.47	0
Spain	1.08	0.51	0.049
Poland	1.01	0.47	0
Netherlands	1.24	0.52	0
Average Europe	1.36	0.48	0.06

In delineating the costs associated with electricity. data are sourced from EUROSTAT. Specifically. electricity prices for non-household consumers falling within the consumption range of 500 MWh to 1999 MWh (band IC) are utilized [104]. Notably. in the project. the battery electric vehicle is expected to be exclusively charged at the fleet operator depot. given the regional mission profile involving a daily travel distance of approximately 300 km. This strategic approach obviates the need for the driver to halt at recharging points during their daily mission. Table 10 provides a succinct summary of the cost per kilowatt-hour (kWh) of electricity. It is imperative to acknowledge that this cost does not solely represent the energy expenditure but includes the anticipated expenses of the fleet operators for installing high-power recharging points (100 kW). The CAPEX for charging stations was obtained from the source [80] published by ICCT. In this study, it is assumed that the charging stations will be installed in existing depots, avoiding any construction or renovation costs. Consequently, the cost considerations are limited to the hardware and installation expenses of the chargers in 2020. Specifically, for overnight charging stations, the unit cost of 100 kW chargers was estimated at €70,000. Given the assumed charger lifetime of 15 years, this results in an additional cost of approximately 5 cents per kWh on top of the raw electricity cost. Furthermore, with regard BEV truck, it is assumed that the truck will be recharged only at the depot, therefore no public charging stations and their costs are included. A scenario in which the BEV recharges through public stations could be incorporated into the final comparison between the two demonstrators and the two baselines in Task 7.4. Additionally, considering the inclusion of a 100kW charger, another scenario featuring different recharging infrastructure power levels (e.g., 350kW) might also be included in Task 7.4.

Table 19-Countries Electricity Price

Country	Price (EURO/kWh)
Germany	0.3019
France	0.1980
Italy	0.4419
United Kingdom	0.3237
Spain	0.3092
Poland	0.2327
Netherlands	0.2458
Average Europe	0.2989

Conversely, hydrogen costs are obtained from the European Hydrogen Observatory of the European Union. elucidating the levelized production costs of hydrogen in Europe across four pathways: Steam Methane Reforming (SMR), Reforming with Carbon Capture and Storage, Grid-Connected Electrolysis, and Renewable Hydrogen. In this study, these values are augmented by incorporating the overheads incurred by distribution and refueling stations, leveraging data from the H2.live portal. This online platform provides weekly updates on hydrogen prices at the pump. The summarized values for the study are encapsulated in Table 11.

Table 20-Hydrogen Cost at Pump EURO/kgH2

Country	SMR	SMR with carbon capture	Grid-connected electrolysis	Green Hydrogen
Germany	5.90	5.34	12.03	7.07
France	5.39	4.84	10.44	6.31
Italy	5.99	5.44	12.39	7.41
United Kingdom	5.67	5.12	8.45	5.34
Spain	5.40	4.84	11.32	6.28

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Poland	5.81	5.25	10.08	5.79
Netherlands	5.04	4.49	13.47	6.15
Average Europe	5.60	5.05	11.17	6.34

Payload Capacity Loss Cost

The Payload Capacity Loss Cost is a component incorporated into the TCO model, specifically addressing situations where alternative technologies such as BEV and FCEV exhibit reduced payload capacities compared to their diesel-powered counterparts. The TCO model regulates the GVW based on truck typology and the operating country, with values sourced from the OECD sheet. It is essential to recognize that permissible maximum weights for lorries can vary across European countries.

In compliance with Council Directive 96/53/EC, zero-emissions trucks are granted the flexibility to exceed the maximum permissible weight limit by up to 2 tons [105]. To evaluate payload capacity, the model subtracts the truck's weight from the GVW, providing the value in tons. The Payload Capacity Loss Cost is incurred when the payload capacity of BEV or FCEV falls below that of diesel trucks.

This cost factor is derived from the need for fleet operators to transport a consistent volume of goods. If the payload capacity of the new technology fleet is inferior to that of diesel-powered counterparts. fleet operators must acquire a proportionate number of additional trucks to handle the same volume of transported goods.

Time Penalty Cost

Like the previously mentioned cost type, the time penalty cost arises when the BEV or FCEV exhibits a longer delivery time compared to the Diesel counterpart. In these scenarios, an additional cost burden falls upon the driver, who must extend the delivery mission due to the utilization of the new technology truck. At present, in the preliminary evaluation of the project, we do not anticipate any increase in delivery time for BEV and FCEV. Therefore, the associated cost is zero. However, should the project reveal a potential increase in delivery time, the model will be adjusted accordingly with new data to assess the corresponding penalty cost.

Residual Value

Determining the residual value of a truck is a multifaceted endeavor, as it hinges not only on the vehicle's age but also on the mileage it has accrued. The proposed approach entails developing a function that encapsulates the truck's depreciation, leveraging data provided by IVG. This method aims to cultivate a comprehensive understanding of the residual value by integrating factors such as age and mileage. By doing so, it endeavors to provide a more precise and nuanced assessment of the truck's long-term value.

8. Results

This section presents the outcomes derived from the methodology outlined in the previous sections. In section 8.1, the results of the LCA are shown, in the section 8.2, the results of the TCO are shown. In sections 8.1.1, the results of the LCA of the baselines are shown in section 8.1.2, the results of the preliminary LCA of the two demonstrators are shown. In section 8.2.1, the results of the TCO of the baselines are shown in section 8.2.2, the results of the preliminary TCO of the two demonstrators are shown.

8.1 LCA results

8.1.1 LCA results of the 2020 diesel baseline trucks

Figure 39 shows the cradle-to-grave climate change results of the 2020 baseline diesel trucks. The 2020 diesel baseline used for long-haul distribution mission profiles is called DIE-LH (first bar in the chart from the left). The 2020 diesel baseline used for regional distribution mission profiles is called DIE-R (second bar in the chart from the left). In this bar chart, results are normalized to the highest score in each category grouping the long-haul vehicles and the regional vehicles in separate groups. Each bar highlights the contribution of raw material acquisition emissions in light blue, manufacturing emissions in dark blue, WWT in light purple, TTW in yellow, maintenance in orange, and EoL in green. For both the baselines, the main driver to the GWP is the WTT phase (66% and 80% for DIE-LH and DIE-R, respectively). The TTW phase has an impact of 31% and 16% in DIE-LH and DIE-R, respectively. The raw material acquisition phase accounts for 2% and 3% in DIE-LH and DIE-R, respectively. The manufacturing, maintenance and EoL phases are negligible (i.e., less than 1%).

Figure 39 also compares the GWP of the two baselines with the GWP of the EMPOWER demonstrators (i.e., FCEV and BEV). The four FCEV scenarios considering different hydrogen production routes (i.e., SMR. SMR + CCS, AE with wind-based electricity mix, AE with fossil-based electricity mix) are shown as well as the two BEV scenarios considering two electricity mixes, namely fossil-based and wind-based. In the case of the EMPOWER demonstrators the most impactful phase is the WTT phase in almost all the demonstrator scenarios. For the BEV demonstrator with wind-based electricity (first bar from the right called BEV wind), the raw material acquisition phase is the main driver and more impactful than the WTT phase. In fact, it accounts for 57% while the WTT phase accounts for 39%. This outcome demonstrates that the more the decarbonization strategy is effective and the GWP reduced, the more the impact shifts towards vehicle production and raw material supply. The TTW phase is nearly zero in all the demonstrators because there are no exhaust emissions but only brake, road, and tire wear emissions.

Compared to the DIE-LH, the FCEV-SMR allows for a GWP reduction of 39%, FCEV-SMR+CCS of 49%, FCEV-AE wind based of 80%, and FCEV-AE fossil based of 17%. Among the FCEV demonstrator scenarios, the scenario in which hydrogen is produced by means of AE with a fossil-based electricity mix is the worst. However, it has a significantly lower GWP than DIE-LH. The scenario in which hydrogen produced by means of AE with wind-based electricity resulted to be the least impactful in terms of GWP.

Compared to the DIE-R, the BEV demonstrator with fossil-based electricity allows for a GWP reduction of 44% while the BEV with wind-based electricity for 89%. The BEV scenario with wind-based electricity resulted as the least impactful scenario in terms of GWP.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

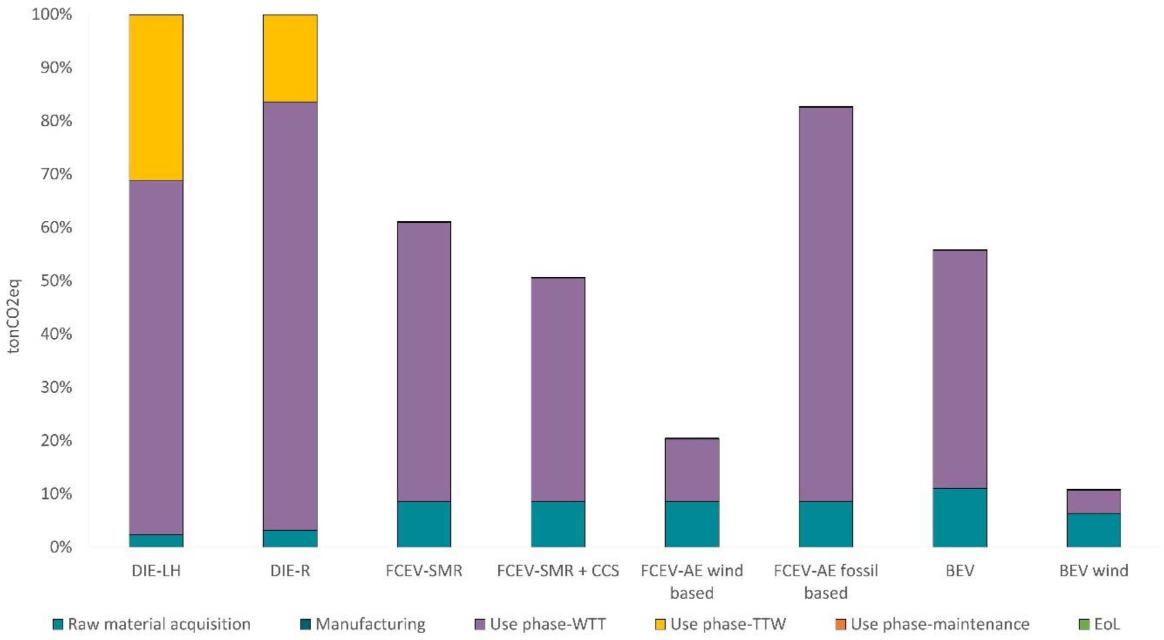


Figure 39: GWP results from cradle-to-grave

Figure 40 shows the comprehensive LCA results of all the investigated vehicles and scenarios in a cradle-to-grave boundary. The impacts are normalized to the highest score in each category grouping the long-haul vehicles and the regional vehicles in separate groups. As with the GWP results (Figure 39), the WTT strongly affects all the impact categories, depending on the impact category considered. The raw material acquisition phase also impacts the environmental results, especially for the EMPOWER demonstrators in particular matter formation, cancer and not cancer human toxicity, acidification, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, ecotoxicity, and land use categories. In the mineral and metal resource use category, the raw materials acquisition phase is the most impactful compared to the others in all the vehicles and scenarios. The EoL phase is negligible in almost all impact categories, except for non-cancer human toxicity, cancer human toxicity and mineral and metal resource use. In addition, the recycling process has significant benefits in terms of circularity due to the avoided production of virgin copper, cobalt, and nickel for the battery in FCEV and BEV scenarios.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

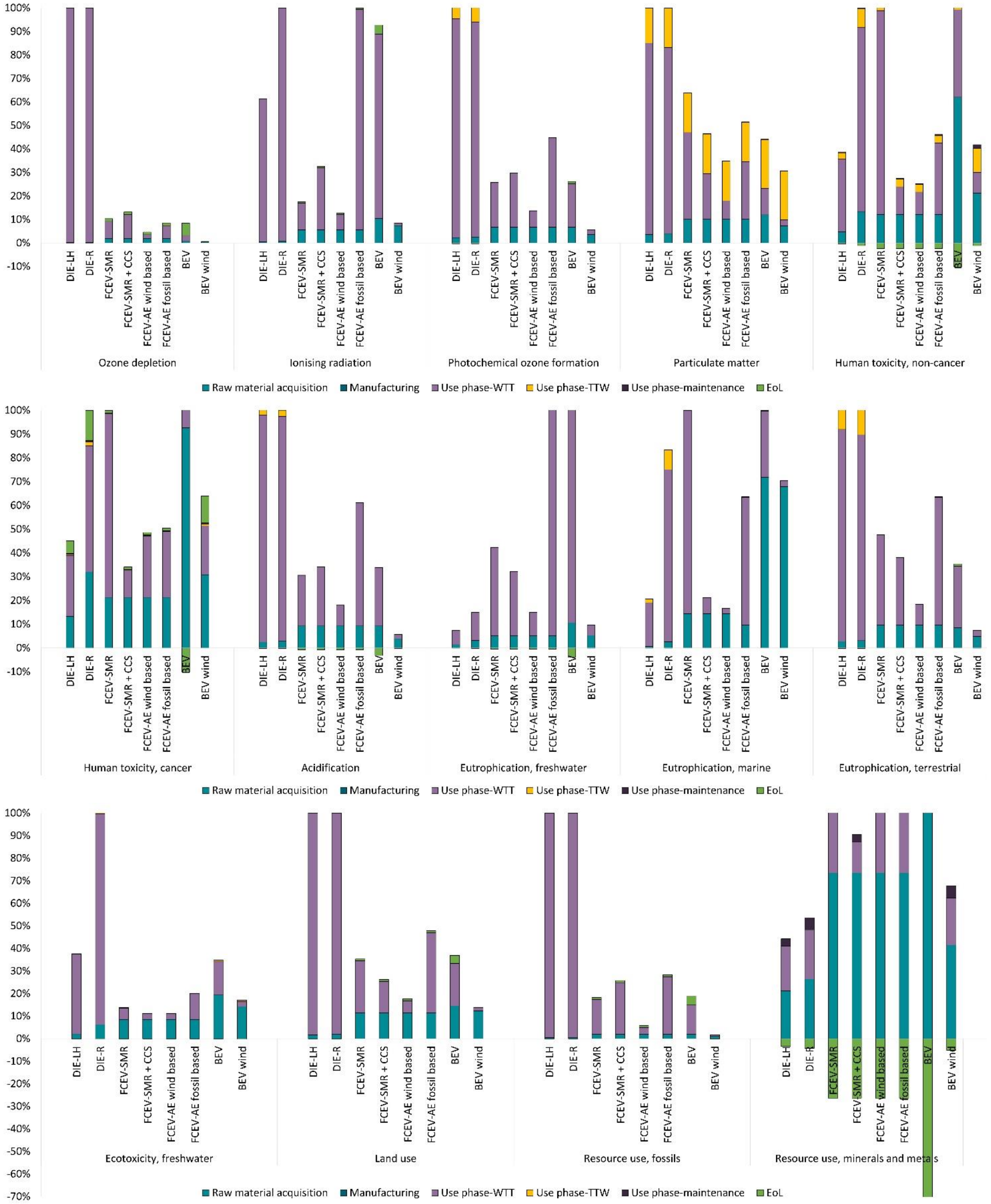


Figure 40: LCA comprehensive results from cradle-to-grave boundary for trucks

8.1.2 Preliminary LCA results of the EMPOWER demonstrators

Figure 41 shows the comprehensive LCA results of one Li-ion battery pack. In terms of climate change, each battery pack has 7377 kg CO_2eq, mainly due to the emissions related to the extraction of raw materials and manufacturing stages (green bars in Figure 41). More specifically, this is due to battery cell production, primarily to cobalt sulphate and, secondly, nickel sulphate, electricity consumption, and lithium carbonate. The EoL stage (purple bars) and more specifically the recycling process increases the climate change impact, but not significantly. The recycling process has significant burdens in ozone depletion, ionising radiation, photochemical ozone formation, terrestrial eutrophication, land use, and use of fossil resources. This is mainly due to the diesel used in the process as fuel, thus, to diesel production. Instead, the recycling process has significant benefits in human toxicity, acidification, freshwater eutrophication, water use, and use of mineral and metal resources. The benefits are mainly due to the avoided production of virgin copper, cobalt, and nickel.

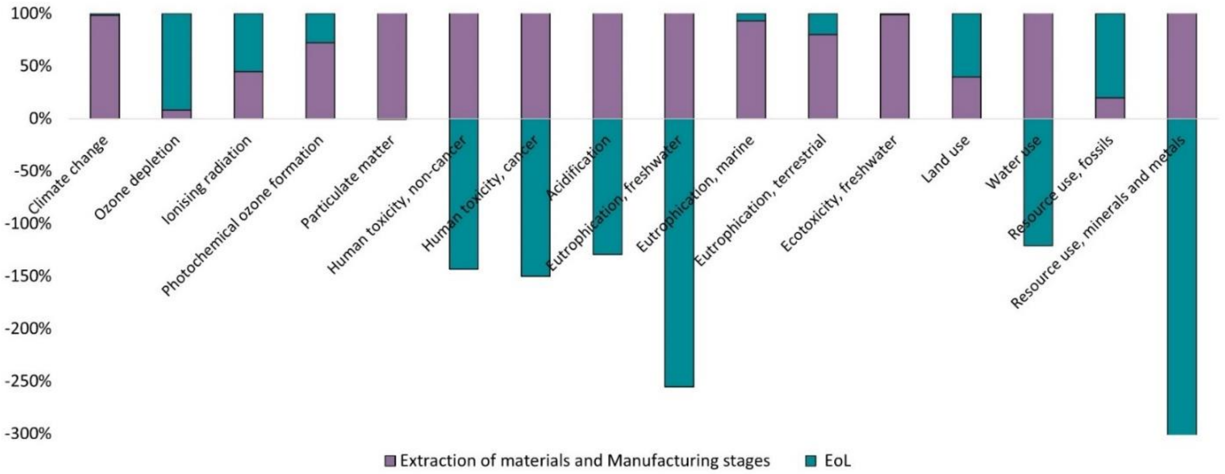


Figure 41: Cradle-to-gate and EoL results for one battery pack.

Figure 42 shows the comprehensive LCA results of different hydrogen production routes. The AE with wind-based electricity mix (light purple bars) represents the best scenario having the lowest impacts in all categories. The AE with fossil-based electricity mix (yellow bars) is the worst scenario in terms of climate change (GWP), ionizing radiation, photochemical ozone formation, acidification, freshwater and terrestrial eutrophication, land use, fossil resource use, mineral and metal resource use categories. The reason is the adoption of the EU electricity mix, which is still based on fossil fuels. Also, the SMR scenario (dark blue bars) represents the worst scenario in the categories of particulate matter formation, cancer and non-cancer human toxicity, marine eutrophication and freshwater ecotoxicity. Lastly, the SMR+CCS scenario (light blue bars) is the worst scenario in the ozone depletion category. The reason is natural gas extraction and supply. In addition, the SMR+CCS reduces the GWP of hydrogen produced through SMR but, at the same time, it raises the impacts in terms of ozone depletion, ionizing radiation, photochemical ozone formation, acidification and fossil resource use categories.

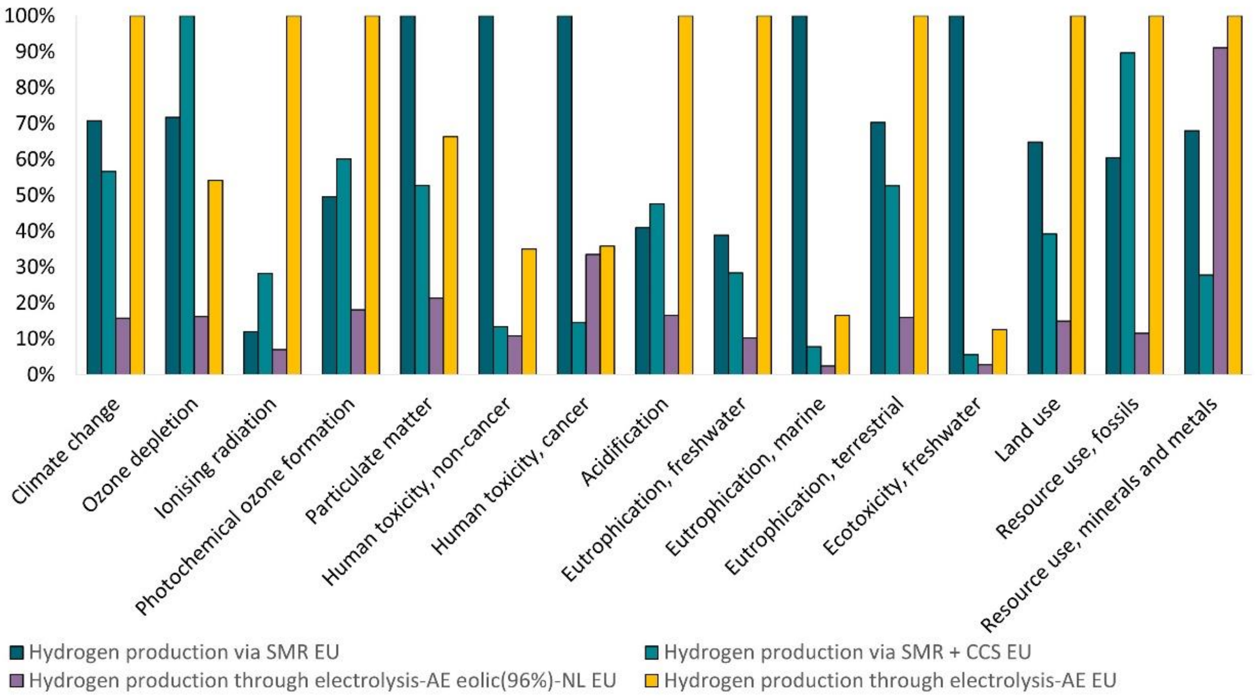


Figure 42: Comprehensive comparison of the environmental impacts of hydrogen production (WTT contribution)

Figure 43 shows the comprehensive LCA results of a fuel cell system in a cradle-to-gate boundary. Each bar highlights the contribution of end plates in orange, bipolar plates in yellow, catalyst in light blue, gasket in green, gas diffusion layer in dark purple, membrane in light purple and BOP in dark blue. The main contribution is provided by the catalyst in almost all the categories except for ozone depletion, cancer and non-cancer human toxicity, mineral and metal resource use categories. The reason is due to the presence of platinum in the catalyst. The BOP is the second contributor in all other impact categories. In the case of ozone depletion, the impact is driven by the water management system, and more specifically by tetrafluoroethylene. For the categories ionizing radiation, water use, fossil resource use, the reason is due to the presence of carbon fibre-reinforced plastic. For the categories cancer and non-cancer human toxicity, water use, fossil resource use, mineral and metal resource use the reason is due to copper contained in the cable conductors. For cancer human toxicity the reason is due to chromium steel contained in the water and fuel management systems. In ozone depletion, the main contributors are BOP, membrane, and gas diffusion layer, and the cause can be attributed to TFE.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

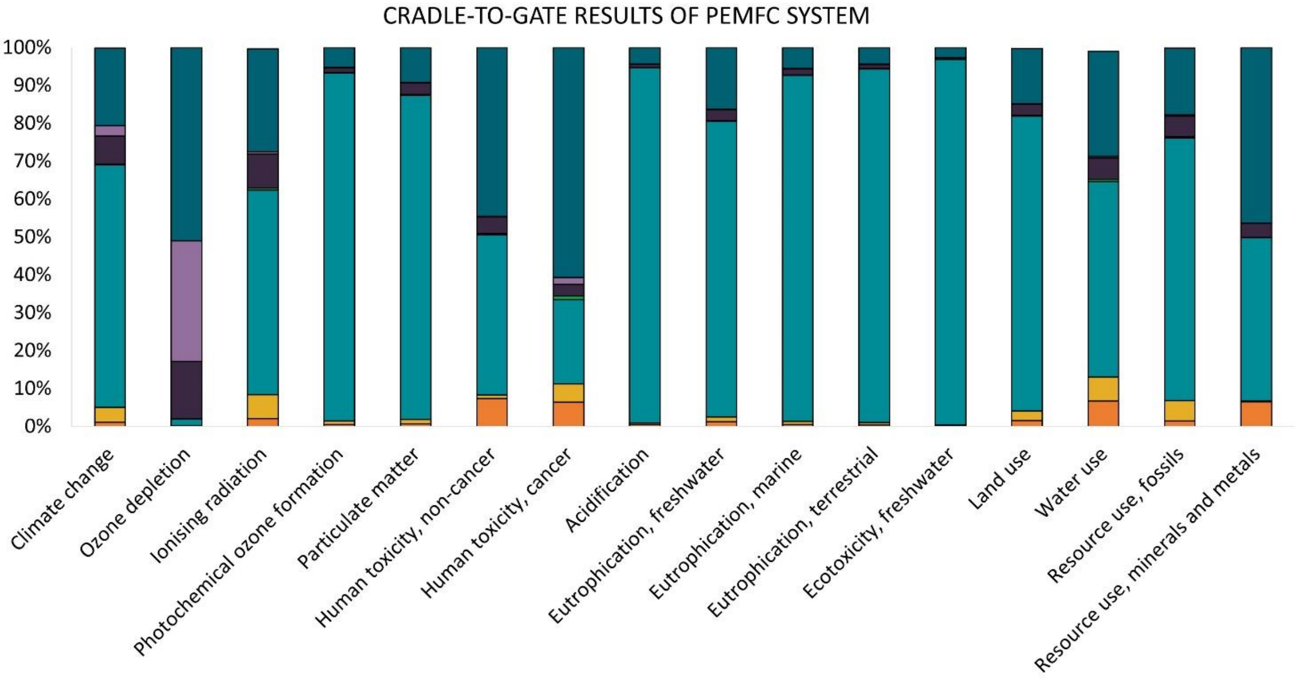


Figure 43: Cradle-to-gate results of the PEMFC system

8.2 TCO Results

8.2.1 TCO results of the 2020 diesel baseline trucks

Overall results

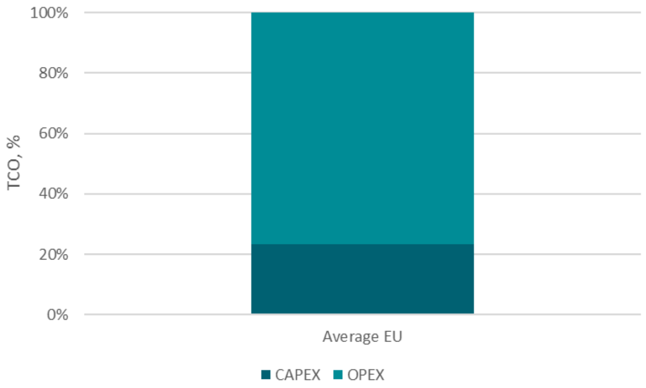


Figure 44-Regional TCO results of baseline diesel

In Figure 44 the economic impact of the regional baseline diesel truck for an average European scenario is shown. It is evident from the figure that the Capital Expenditure (CAPEX), inclusive of the purchase cost and the residual value (considered negative since it denotes revenue for the fleet operator upon selling the truck). This underscores a crucial point: Operational Expenditure (OPEX) overwhelmingly dominates the expenses incurred by the fleet operator throughout the entire lifecycle.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

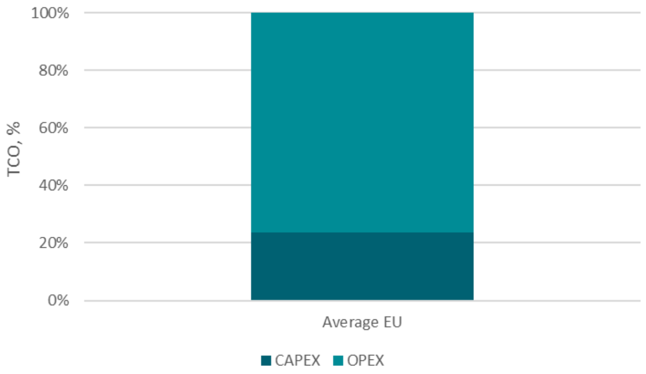


Figure 45-Long-haul TCO results of baseline diesel truck

Figure 45 illustrates the comprehensive outcomes derived from assessing a long-haul baseline diesel truck emblematic of the year 2020. There are not many differences in terms of the split between CAPEX and OPEX

Further scrutiny of the long-haul results unveils a breakdown of costs in Figure 46. Here, we observe that the driver cost emerges as the most significant. constituting 27% of the TCO in this typical scenario. Following closely are the Purchase cost at 26.7% and the energy carrier cost at 26.6%. This underscores the significance of these expenses, as they collectively surpass the 50% mark in the TCO. Notably, the driver cost is influenced by minimum wage legislation or drivers' unions, lies beyond the direct control of the fleet operator.

Moreover, taxes account for 11% of the total cost, while maintenance represents 10%. Interestingly, the residual value obtained from selling the truck at the end of the considered lifespan (700,000 km) constitutes a mere 3%. Consequently, the depreciation of the diesel truck emerges as a substantial factor, emphasizing its notable impact on the financial dynamics.

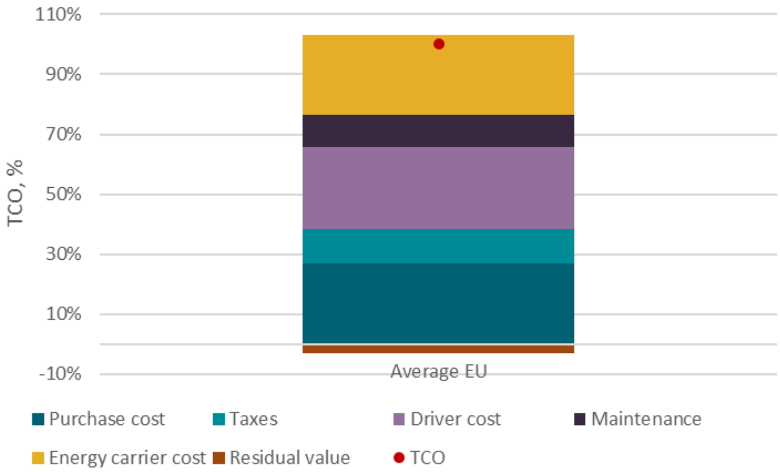


Figure 46-Long-haul TCO results with granularity

As previously outlined. the developed methodology aimed to assess economic impacts across various countries. considering distinct Operational Expenditure (OPEX) components such as energy carrier costs, driver expenses, and taxes. Consequently, a sensitivity analysis was conducted to illustrate disparities among

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

countries, based on an average scenario representative of Europe with typical costs for each expenditure category.

Figure 47 presents the results of this sensitivity analysis across seven selected countries. Given the assumption that Capital Expenditure (CAPEX), comprising purchase costs and residual values, remains constant across countries, differences in TCO between the average EU scenario and country-specific values primarily reflect variations in OPEX.

The analysis reveals that Poland exhibits the lowest TCO. showcasing a reduction of over 26% compared to the average EU scenario. Conversely, the Netherlands emerges as the most cost-intensive scenario, with TCO nearly 20% higher than the EU average.

Among the remaining scenarios, Italy, Spain, Germany, and the United Kingdom demonstrate TCOs around ±10% relative to the EU average. Notably, the French scenario emerges as the second most cost-intensive among those evaluated.

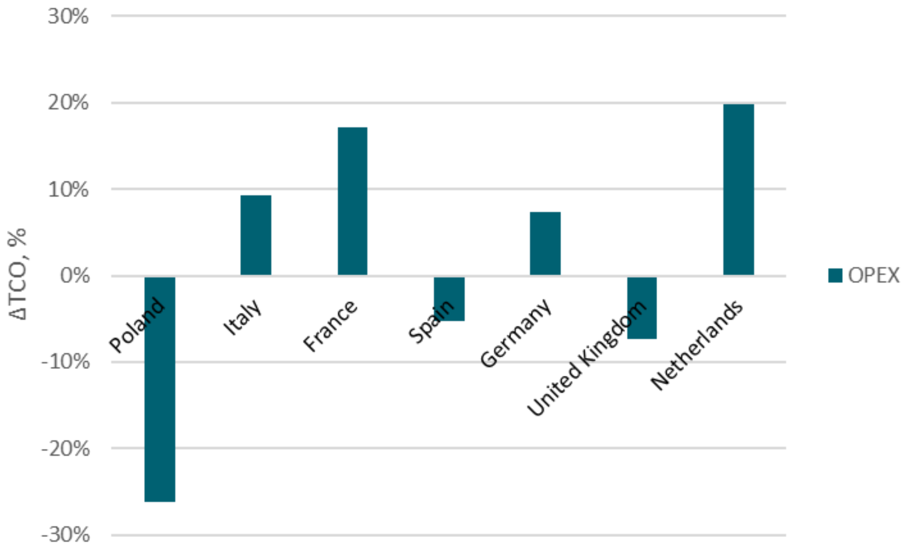


Figure 47-Long-haul sensitivity analysis over countries

A more detailed examination of the results can be achieved by analysing them per cost type, as illustrated in Figure 48. It becomes evident that the majority of differences stem from variations in taxes and driver costs compared to the average EU scenario. Interestingly, the impact of energy carrier costs on the overall assessment across the full lifecycle appears less significant.

Notably, energy carrier costs exhibit variation across scenarios. For instance, France and Spain display lower energy carrier costs due to a comparatively reduced energy carrier cost per kilowatt hour than the average EU value. Conversely, scenarios in Germany, the UK, and the Netherlands feature higher energy carrier costs, attributed to elevated energy prices exceeding the average European value.

These insights underscore the nuanced interplay between localized factors, such as tax regulations, labor costs, and energy prices. in shaping the economic dynamics of fleet operations across different European contexts. By dissecting the results per cost type, a deeper understanding emerges, facilitating informed decision-making and strategic planning within the realm of transportation logistics.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

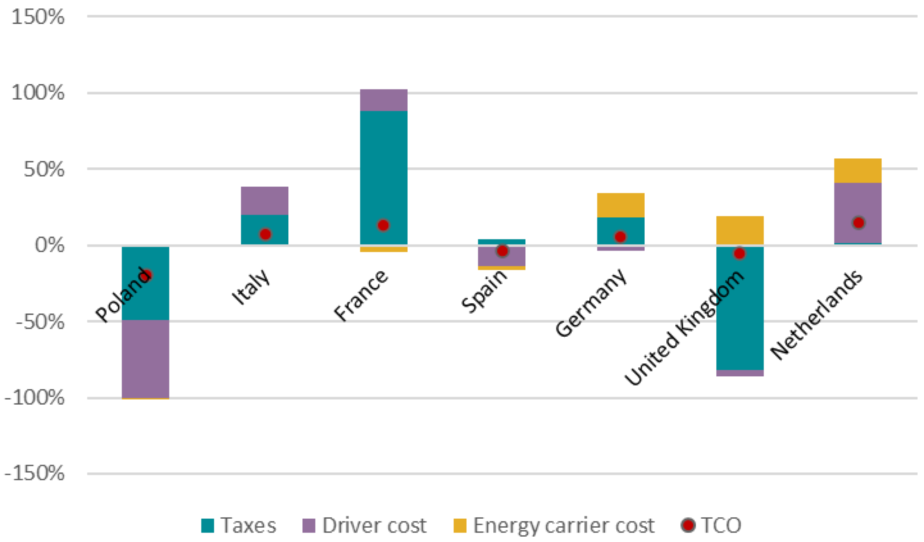


Figure 48-Long-haul sensitivity analysis with granularity

Taxes and road costs

Looking at the taxes and costs related to road use, we can go into detail analysing the single impact of this cost type over the total taxes cost type to explain better which is the main contributor of the taxes cost type.

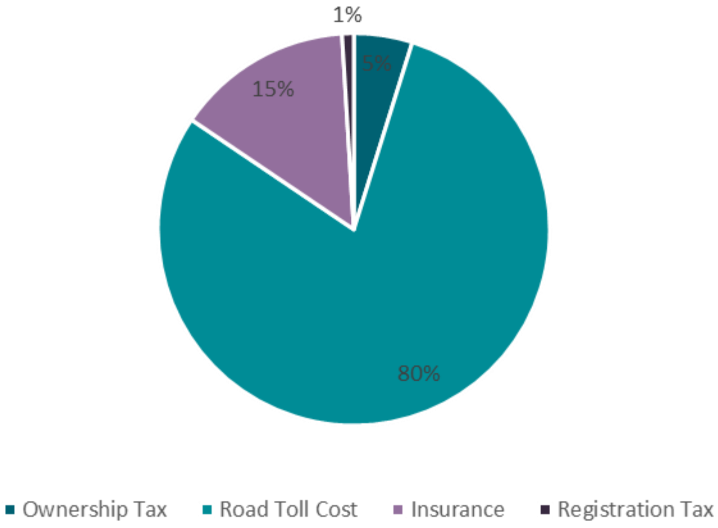


Figure 49-Long-haul baseline taxes and road cost breakdown

Figure 49 underscores that the foremost contributor to both taxes and road-related costs is the expenditure on road tolls, accounting for a staggering 80% of the total taxes incurred. This dominance can be attributed to the inherent operational characteristics of long-haul trucking, where a substantial portion of daily missions is dedicated to traversing highways. The reliance on these routes renders highway road toll expenses the principal driving force behind tax expenditures. The prominence of road toll costs is further accentuated by their direct correlation with the distance covered on highways, amplifying their impact on overall tax burdens. Following behind, the insurance cost emerges as the second significant contributor, constituting 15% of the total taxes and road costs. In contrast, the registration taxes are characterized by their one-time imposition and relatively modest value, representing a mere 1% of the overall tax expenditures. These findings underscore the pivotal role of road toll expenses in shaping the economic landscape of long-haul trucking operations.

When examining the regional baseline diesel truck, it becomes evident that road toll costs have a reduced impact compared to the long-haul baseline. This is primarily due to the reduced time regional delivery trucks spend on highways, as illustrated in Figure 50. Consequently, with road costs being less significant, the proportionate impact of insurance expenses increases, accounting for up to 26% of the total cost typology. A similar pattern emerges concerning ownership tax. Ultimately, the overall cost is less burdensome compared to the long-haul baseline.

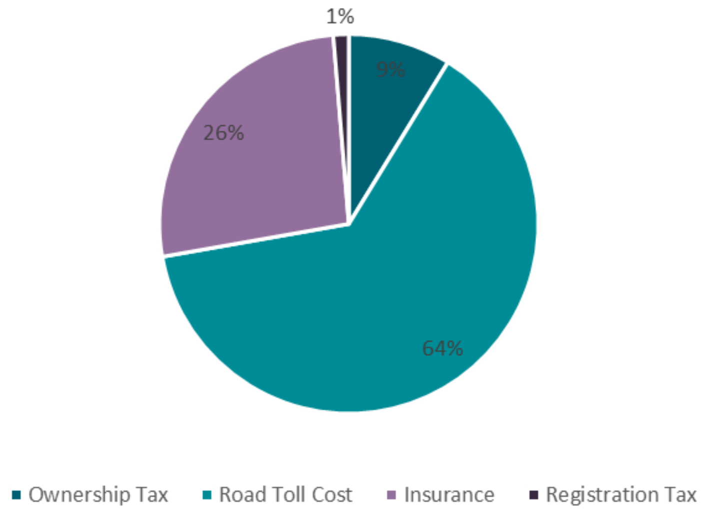


Figure 50-Regional baseline taxes and road cost breakdown

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Figure 51-Long-haul sensitivity analysis over taxes and road use costs

Figure 51 provides clarity on the disparities observed among scenarios concerning the specific cost type of taxes and road use costs. A grouped bar chart effectively illustrates these distinctions by highlighting the relative differences in costs compared to the average European scenario. The total difference of each country's scenario relative to the average is also presented for comprehensive analysis.

As highlighted in Figure 49, road tolls emerge as the primary contributor to total costs of this cost type. Consequently, in countries where road tolls are low or non-existent, such as the United Kingdom, the associated cost is significantly lower compared to the average scenario. Conversely, in nations like Italy, France, and Germany, where road tolls are substantial. the percentage delta in costs is notably higher.

Indeed, given the assumption of uniform insurance costs across scenarios, the delta cost for insurance remains zero, rendering its contribution negligible in the sensitivity analysis. Consequently, it is not depicted in the analysis, as it does not contribute to variations in costs across different scenarios.

Driver Cost

The driver cost, as illustrated in Figure 46, is the most impactful cost over the full life cycle of the truck. Going into detail, we can divide this cost into three contributions: the average salary which is the amount directly given to the driver by the fleet operator, the travel allowances, and the social contribution part. As highlighted in Figure 52 most of the cost is due to the average salary, but a non-negligible fraction is due to the allowances and the social contribution. Therefore, these two costs represent 42% of the total driver cost in the average European scenario.

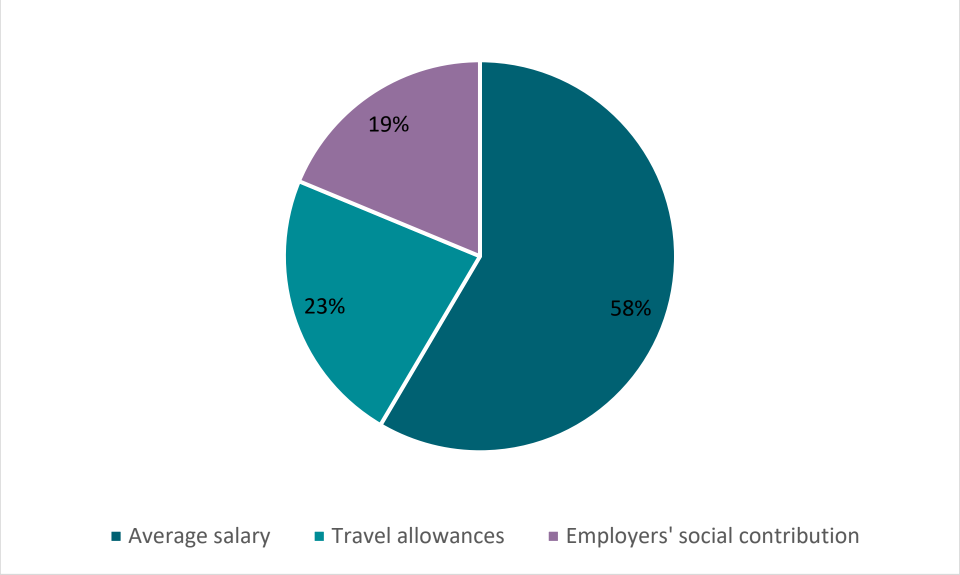


Figure 52-Driver cost breakdown Average EU scenario

Another aspect to be highlighted is the sensitivity analysis and the different driver costs across the countries evaluated. Hereafter in Figure 53, it is shown contributor by contributor the difference in terms of driver cost concerning the average European scenario.

Figure 53- Long-haul geographical sensitivity analysis over driver cost

One notable observation is the variation in driver costs across scenarios, particularly in Italian, French, and Dutch contexts, where higher wages contribute to elevated expenses in this cost category. Upon closer examination, it becomes apparent that the social contributions in the Netherlands are 1.5 times higher compared to the average scenario, further exacerbating driver cost differentials.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Contrastingly, Poland stands out for achieving over 50% reduction in costs, primarily attributable to lower wages and social contributions. Despite incurring higher travel allowance expenses, Poland's overall cost reduction underscores the significant impact of labor-related factors on total expenditures.

Maintenance

Maintenance costs are intricately tied to the distance traveled, exhibiting consistency across both baseline diesel trucks and geographical locations due to the assumption of uniform values for each contributor within the model. As anticipated, repair and preventive maintenance emerge as the predominant drivers, constituting a substantial 65% of the total maintenance expenditure.

Following are expenses related to tires, encompassing both those belonging to the truck and trailer, which collectively contribute up to 28% of the overall maintenance costs. Lastly, expenditures associated with lubricant oil, and AdBlue refilling round out the maintenance expenses.

This breakdown is shown in Figure 54, underscores the significant role of routine maintenance activities, particularly repair and preventive measures, in shaping the economic dynamics of fleet operations.

There are no discernible differences between the two baselines concerning maintenance cost typology. This is because maintenance costs are directly proportional to the kilometers driven. Therefore, the percentage impact of the subcategories remains consistent. Consequently, the overall results under the assumption of no disparity in maintenance between the two vehicles will remain unchanged. The final actualized results will indeed differ due to the variance in lifespan caused by the annual mileage of the two vehicles.

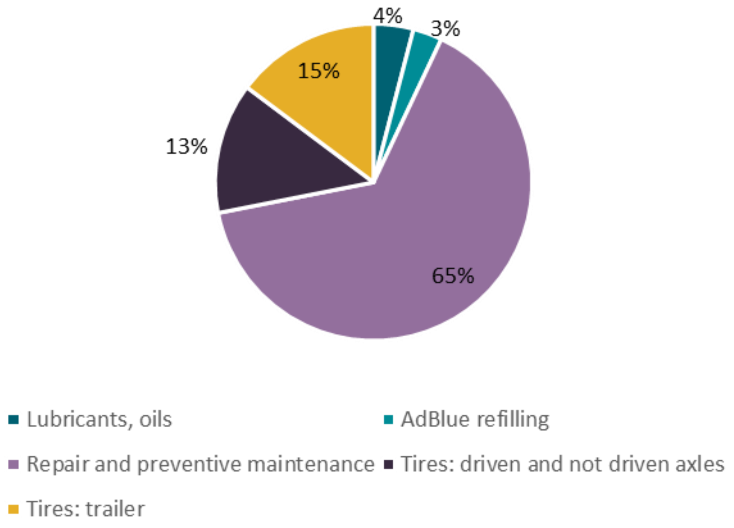


Figure 54-Maintenance Breakdown

Energy carrier cost

Figure 55 shows the energy cost breakdown of the diesel truck in the average European scenario. The total energy carrier cost is divided into three contributions: Raw material, taxes, and excise refund.

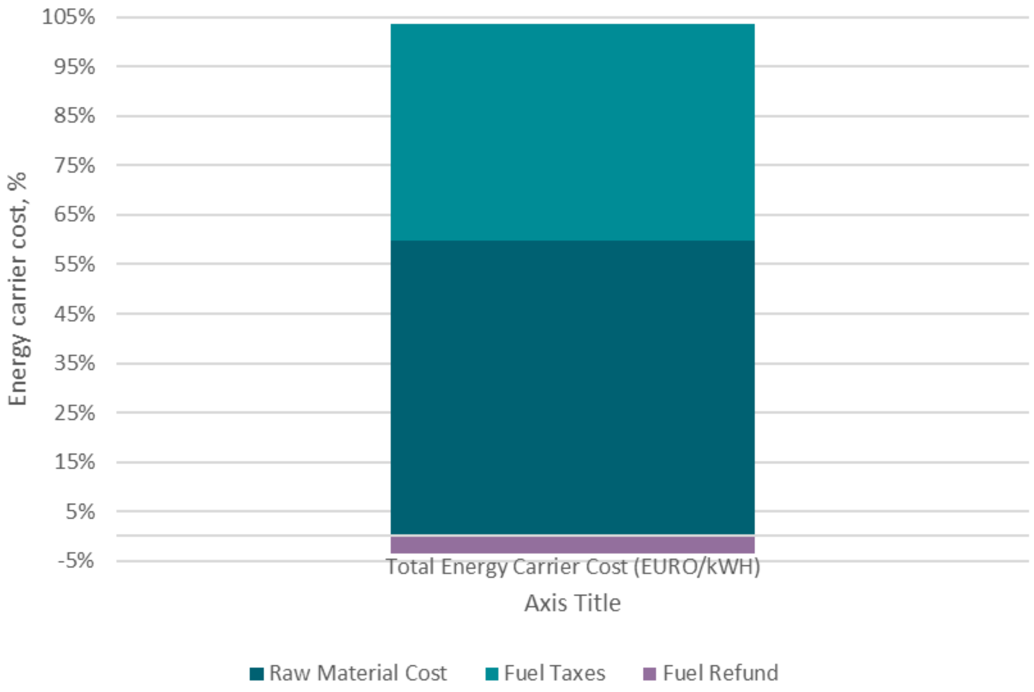


Figure 55-Diesel cost breakdown

In the analysis of the breakdown of energy carrier costs for diesel trucks, raw material expenses constitute a significant portion, ranging up to 60% of the total energy cost per kilowatt-hour (kWh). Taxes also play a substantial role, contributing up to 44% of the total cost. However, refund costs are comparatively minimal, as most countries do not heavily implement excise refunds. Notably, France and Italy stand out as exceptions, with significant excise refunds per liter of diesel purchased. Even in energy carrier cost, there are no differences between the two baselines since the two are diesel trucks.

8.2.2 Preliminary TCO results of the EMPOWER demonstrators

The evaluation of the two demonstrators is the focal point of Task 7.4, occurring after the manufacturing and testing phases of the subsystems that will be integrated into the ZE HDVs. Below are the preliminary results of the comparison between the two baselines and the two demonstrators along with some projection scenarios for the years 2030 and 2050. These scenarios consider the reduction of subsystem costs and the price of the energy carrier. However. it is important to note that these scenarios are not exhaustive, Task 7.4 emphasizes a comprehensive evaluation of the projections for the two demonstrators, encompassing optimistic and pessimistic scenarios. This approach will enable project partners and policymakers to gauge a range of total ownership costs within which the two demonstrators may fall in the future.

BEV overall results average European scenario

The preliminary comparison between the BEV demonstrator and the regional baseline diesel trucks was conducted using the 2020 baseline reference year. Figure 56 illustrates the disparities in CAPEX and OPEX in the average European scenario. The CAPEX of the BEV is nearly double that of the baseline diesel truck primarily due to the high cost associated with the battery system and its integration into the truck. As previously mentioned, CAPEX comprises the purchase cost and residual value. For this preliminary evaluation, the residual value of the BEV was sourced from [58] which considers the residual value of the battery pack to be 85% of the initial value. However, estimating the residual value in ZE HDVs entails uncertainties as no ZE HDVs have reached the end of their lifecycle yet. Therefore, Task 7.4 will assess various scenarios for the residual value, encompassing optimistic and pessimistic outcomes related to ZE HDVs.

Despite the technology considered, the split between CAPEX and OPEX remains largely consistent. For instance, while CAPEX represents nearly 25% of the TCO for the regional baseline vehicle, it represents around 27% of the BEV truck. Consequently, OPEX remains the predominant factor in the TCO for trucks. In the diesel truck, OPEX accounts for 77% of the TCO, while in the BEV it represents 73%, slightly lower but still the primary contributor by a significant margin.

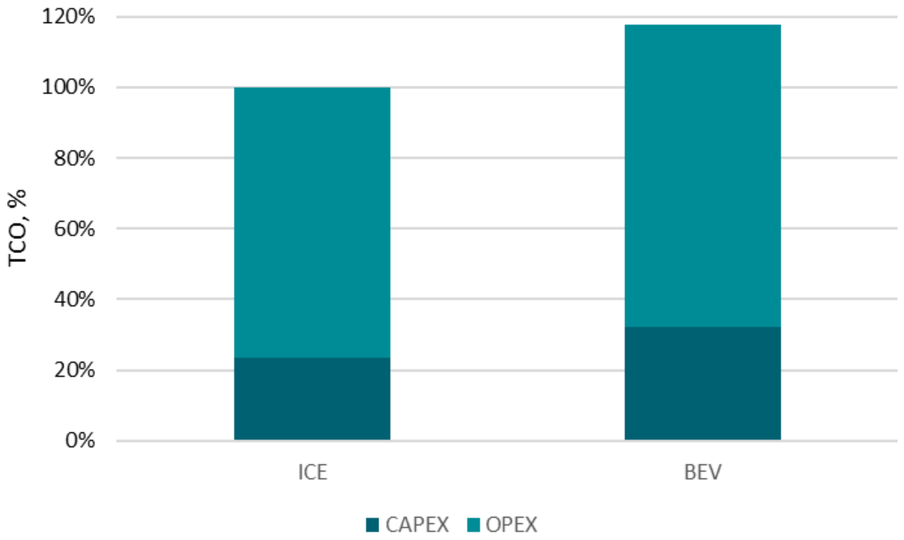
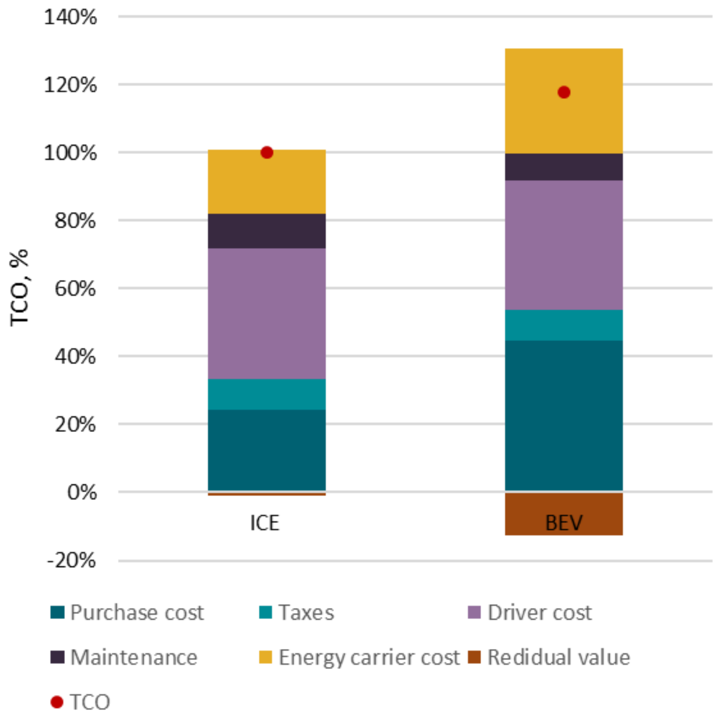


Figure 56-Preliminary evaluation BEV demonstrator

When delving into cost types, it is crucial to highlight the main differences to make the obtained results understandable. For example, the purchase cost emerges as one of the most significant cost categories in TCO comparisons between the two technologies. This is because the driver cost is assumed to be the same for both trucks. Therefore, reducing the purchase cost is essential to achieve cost parity. This cost reduction can be achieved through mass production of the battery pack in the coming years and a decrease in integration costs into the vehicle.

Another noteworthy aspect is the overall energy carrier cost of the BEV, which is higher compared to the regional baseline due to the recent increase in electricity prices. This cost type is not dependent on the manufacturer but significantly impacts the BEV's TCO. Hence, policymakers need to thoroughly consider this aspect, as it represents more than 25% of the BEV's TCO. Exploring financial incentives provided by governments is also something to be evaluated in projection scenarios, possibly as one of the scenarios that will be analyzed in Task 7.4, to assess the potential contribution from European governments.

The reduction in maintenance costs for the BEV compared to the baseline is anticipated, as supported by existing literature. This reduction is attributed to the fewer components in BEVs, potentially leading to a decreased risk of component failure. However, despite the reduction exceeding 25% compared to the baseline, its overall impact is relatively modest. Maintenance costs represent only around 10% of the TCO for the BEV truck, aligning with our previous analysis of the baseline. Consequently, the impact of maintenance, as observed in the baseline, seems to be not as significant for the BEV



.

Figure 57-Preliminary evaluation BEV demonstrator with granularity

BEV truck projection scenarios

Figure 58 illustrates projection scenarios where BEV subsystem costs are expected to decrease, alongside a decline in electricity prices in the coming years. It is evident from these scenarios that the BEV, under analysis, could achieve TCO parity with the regional diesel delivery truck by 2030. This projection is based on the anticipated reduction in electricity prices and a significant decrease in the purchase cost of the BEV.

It is important to note that these scenarios do not include any financial benefits, such as incentives from European governments for ZE HDVs or penalties for ICE vehicles. The inclusion of such financial benefits could further facilitate reaching cost parity and potentially lead to a reduction in TCO compared to the baseline diesel truck. Therefore, exploring these possible financial benefits is crucial for a more comprehensive understanding of the potential outcomes and implications for the BEV in the market. Anyway, the impact of OPEX remains the most important over the TCO of the trucks.

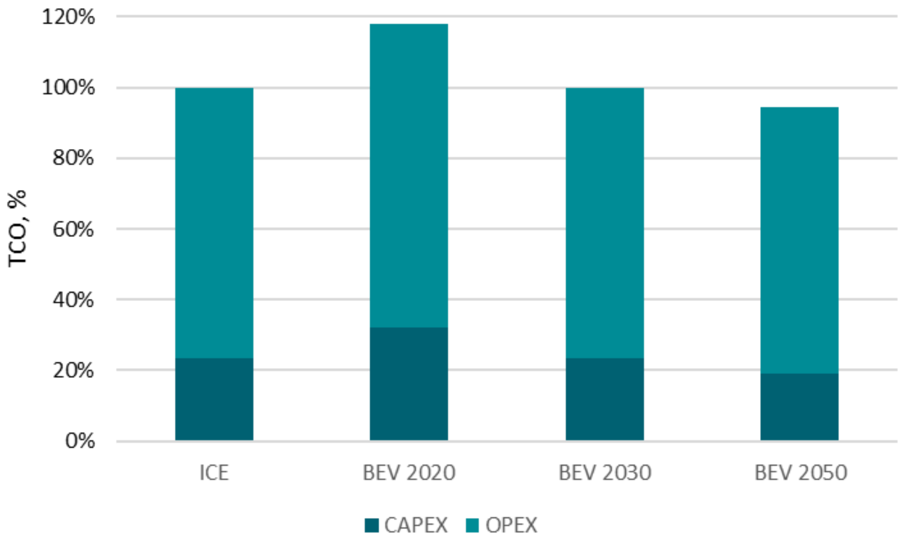


Figure 58-BEV future projection scenarios

When analyzing cost types, it is evident that the two primary contributors to the TCO reduction of the BEV truck are the purchase cost and the energy carrier cost. These costs are expected to decrease in the coming years. While maintenance costs are not anticipated to decrease further, they are assumed to remain constant. The energy carrier cost is projected to decrease due to the expected reduction in electricity costs resulting from the transition from fossil fuel to renewable energy sources. This shift will lead to a reduction in energy production costs, benefiting the final customer, in this case, the fleet operator.

To provide a comprehensive assessment, Task 7.4 should include additional scenarios considering pessimistic and optimistic projections. This approach will offer a range of expected values that we can anticipate in the next decades, allowing for a more robust understanding of potential outcomes.

Indeed, the expected decrease in purchase costs over the coming years stems from the anticipated mass production of ZE HDVs, leading to economies of scale. This phenomenon will drive down the costs of batteries and subsystems integrated into BEV trucks. Consequently, by 2050, it is foreseen that the BEV truck will be less expensive than the baseline diesel truck. This trend underscores the potential for substantial cost savings and enhanced affordability of BEV trucks over time.

Moreover, a comprehensive evaluation of pessimistic and optimistic scenarios for this cost type will be conducted in Task 7.4. This evaluation will consider various trends in subsystem cost reductions, ranging from pessimistic to optimistic outlooks. Such an approach will provide a complete understanding of potential future trajectories and their implications for the adoption of BEV trucks.

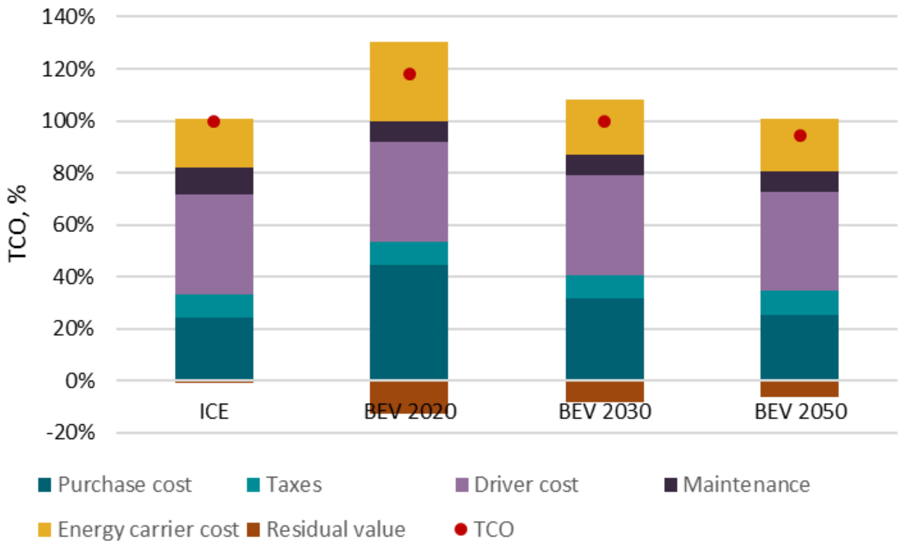


Figure 59-BEV future projection scenarios with granularity

In summary, the cost-effectiveness of the regional Battery Electric Vehicle (BEV) truck hinges on two key factors: the reduction in subsystem costs, including the battery, electric motor, and transmission, and the decline in electricity prices. The projected decrease in purchase costs, driven by mass production and economies of scale, is anticipated to make BEV trucks more affordable compared to diesel counterparts by 2050. Additionally, the shift towards renewable energy sources is expected to contribute to a decrease in energy carrier costs, further enhancing the economic viability of BEV trucks. Task 7.4 will delve deeper into various scenarios, encompassing pessimistic and optimistic outlooks on subsystem cost reductions, providing a comprehensive understanding of potential future trends and their impact on the adoption of BEV trucks.

FCEV truck overall results for an average European scenario

In evaluating the Fuel Cell Electric Vehicle (FCEV) truck, considerable attention is given to the origin of hydrogen production, which greatly influences the TCO. Four distinct hydrogen scenarios are explored: Steam Methane Reforming, Steam Methane Reforming with Carbon Capture and Storage, hydrogen from the electricity grid, and green hydrogen derived from renewable energy sources. The disparity among these scenarios primarily stems from variations in hydrogen costs. As depicted in Figure 60, comparing these technologies underscores the present-day higher costs associated with FCEV subsystems and their integration into vehicles. The CAPEX for FCEVs exceeds twice that of the baseline truck, primarily due to the higher residual value of FCEVs, influenced by the residual value of the Fuel Cell (FC) system and hydrogen tank. Moreover, OPEX is currently more expensive than the baseline, largely attributable to the high costs of hydrogen across all considered pathways. Notably, the pathway producing hydrogen from the grid emerges as the costliest, driven by elevated electricity prices in recent years, nearly doubling the FCEV truck's TCO compared to the baseline. Conversely, green hydrogen, with its lower costs, nearly equalizes the pathway's expense with those associated with steam methane reforming processes.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

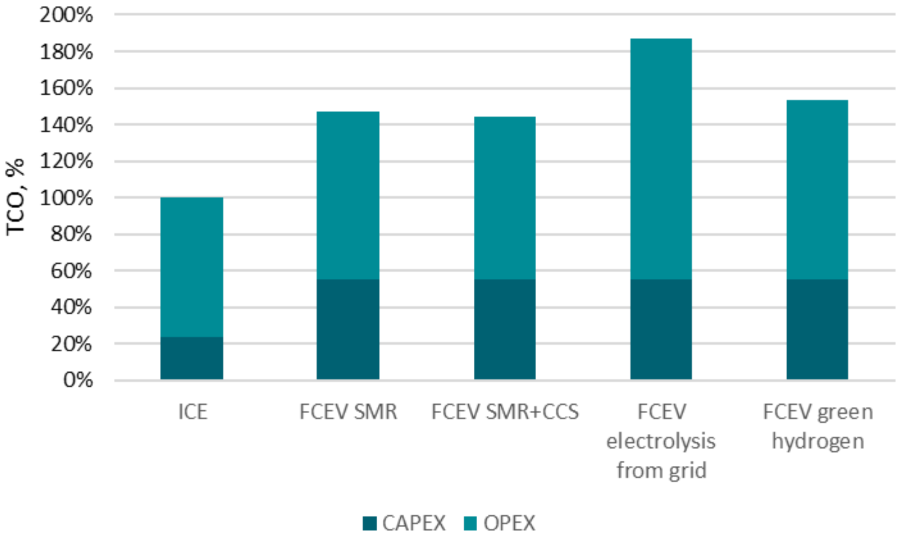


Figure 60-FCEV truck preliminary evaluation for an average European scenario

Examining the results presented per cost type in Figure 61, the primary difference between the two technologies lies in the purchase cost and the energy carrier cost. The high purchase cost of the Fuel Cell (FC) system and the hydrogen tank is largely attributed to the low production volume worldwide. Similarly, the energy carrier cost significantly exceeds that of the baseline diesel truck, even when considering grey and blue hydrogen, which are not optimal solutions for decarbonizing the transport sector. Notably, hydrogen produced from the electricity grid emerges as the most expensive option, driving up the TCO substantially. To address these cost disparities, the focus must be on reducing the costs associated with the subsystems involved in the Fuel Cell Electric Vehicle (FCEV) truck and lowering the overall cost of hydrogen production.

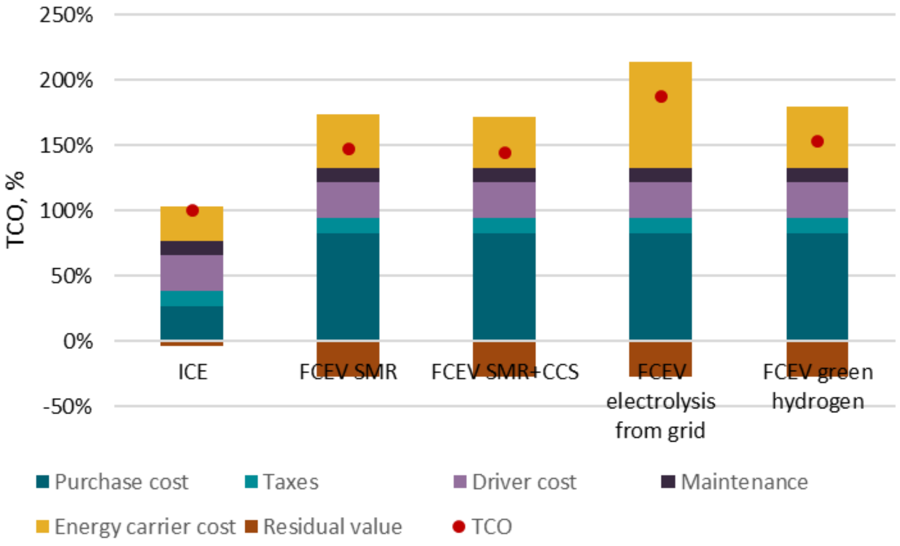


Figure 61-FCEV truck preliminary evaluation for an average European scenario with granularity

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

FCEV future projection scenarios

Below are the projected scenarios for the Fuel Cell Electric Vehicle (FCEV) truck, facilitating a comparison with the diesel Internal Combustion Engine (ICE) truck over the upcoming years. These scenarios incorporate reductions in Fuel Cell (FC) system and hydrogen tank costs, along with decreased hydrogen production costs due to mass production, as illustrated in Figure 62. Notably, as the evaluated baseline diesel truck pertains to the year 2020, there is no escalation in costs resulting from potential carbon taxes or strengthened EURO 7 emissions standards, nor is there an increase in diesel fuel costs. Moreover, this preliminary evaluation does not include financial incentives for ZE HDVs or penalties for diesel trucks.

Given these factors, it is anticipated that the FCEV truck will remain more costly up to 2050 when considering green hydrogen. However, if blue hydrogen is utilized, TCO parity can be achieved as early as 2030, demonstrating a promising pathway toward cost-effectiveness soon.

Consequently, to effectively decarbonize the transport sector, especially the long-haul segment, active intervention by European governments seems to be imperative. This intervention could involve subsidies to reduce purchase and hydrogen production costs for FCEV trucks, or penalties for diesel trucks, thereby making the FCEV truck cost-effective.

In the comprehensive evaluation of the demonstrators, Task 7.4, we will explore the possibility of financial incentives and penalties through various scenarios. This approach will allow us to assess multiple possibilities and demonstrate the range of potential outcomes, thereby raising awareness among stakeholders about the risks and challenges associated with FCEV adoption in the future.

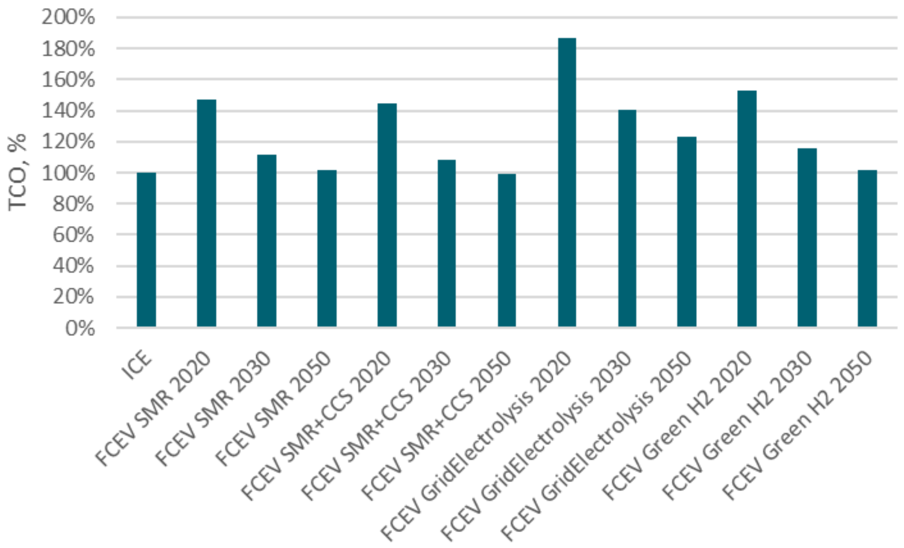


Figure 62-Projection scenarios for FCEV truck over the evaluated pathways

The preliminary economic projection scenarios of Fuel Cell Electric Vehicle (FCEV) trucks present a complex yet crucial aspect of transitioning toward sustainable road transportation solutions. A thorough analysis encompasses various factors, including the reduction in subsystem costs, such as the Fuel Cell (FC) system and hydrogen tank, alongside decreased hydrogen production costs due to mass production. These projections are illustrated in Figure 63. Importantly, the evaluation compares FCEV trucks with diesel-ICE trucks over the coming years, with the baseline diesel truck referencing the year 2020. In the evaluated scenario, this baseline omits potential escalations in costs resulting from carbon taxes, strengthened EURO 7 emissions standards, or increases in diesel fuel costs. Moreover, financial incentives for ZE HDVs or penalties for diesel trucks are not considered in this preliminary evaluation.

The results underscore a significant disparity between FCEV and diesel trucks, particularly in terms of purchase and energy carrier costs. The high purchase cost of FC systems and hydrogen tanks, attributed to low global production volumes, is a significant contributor to the overall cost difference. Additionally, energy carrier costs, even with options like gray and blue hydrogen, exceed those of the baseline diesel truck due to elevated electricity prices and hydrogen production costs. Notably, hydrogen sourced from the electricity grid emerges as the most expensive option, amplifying the overall TCO of FCEV trucks.

However, amidst these challenges, a promising pathway toward cost-effectiveness emerges with the utilization of blue hydrogen. With projections indicating TCO parity as early as 2030, blue hydrogen offers a compelling solution for decarbonizing the transport sector, particularly in long-haul applications. This positive outlook underscores the importance of active intervention by European governments, necessitating subsidies to reduce purchase and hydrogen production costs for FCEV trucks or penalties for diesel trucks. Such interventions would pave the way for a more sustainable and economically viable transition to FCEV technology.

In the comprehensive evaluation of the demonstrators, Task 7.4, various scenarios will be explored to assess the impact of financial incentives and penalties. By examining multiple possibilities, stakeholders will gain a nuanced understanding of the risks and challenges associated with FCEV adoption, ultimately facilitating informed decision-making in the pursuit of sustainable transportation solutions.

9. Conclusions

The escalating worldwide CO_2 emissions and rising temperatures underscore the urgent necessity for a significant decarbonization in our economies and ways of living. Among others, the transport sector requires a significant transition to zero tailpipe emissions to accomplish complete carbon neutrality by 2050. To reach the prospected goals, ZE HDVs with a similar performance as conventional HDVs are necessary. Nevertheless, the challenge is improving their competitiveness against their conventional counterparts. Hence, both environmental and economic considerations should be simultaneously considered.

In this context, the objective of EMPOWER is to deliver two modular and flexible ZE HDVs of VECTO group 9 with a GVW of at least 40 tons, both at TRL 8. One of the demonstrators will be a FCEV suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km. The second one, being a BEV, will be designed for regional distribution mission profiles with a maximum unrecharged driving range of 400 km. Within the EMPOWER project, a fundamental objective of WP1 (Task 1.4) is to develop the LCA and TCO models of a 2020 baseline diesel truck LCA model. The baseline is intended to be used as a reference point for comparison with the two novel demonstrators that will be developed during the project. The analysis of the two demonstrators will be performed during WP7 (Task 7.4) with data from the actual EMPOWER developments. Furthermore, preliminary estimations of the LCA and TCO of the two demonstrators have been performed. For the TCO, a production volume of more than 10,000 trucks per year has been assumed, trying to anticipate and estimate the cost reduction due to mass production.

In this study, a cradle-to-grave LCA study has been performed considering its full life cycle (e.g., production, use phase, end of life, with all influencing parameters included in the analysis: materials, resources, processes, etc.). Two baseline diesel trucks have been identified as representative of the EU 2020 market situation, one for the regional (DIE-R) and one for the long-haul (DIE-LH) distribution mission profile. Both the EMPOWER demonstrators, one FCEV for long-haul applications and one BEV for regional applications, have been evaluated and compared to the baselines. For the FCEV, the analysis covers four distinct scenarios (FCEV-SMR, FCEV-SMR+CCS, FCEV-AE wind, FCEV-AE fossil-based) considering different hydrogen production routes (i.e., SMR, SMR+CCS, and AE powered by wind- or fossil-based electricity). For the BEV demonstrator, the analysis covers two scenarios considering different electricity mixes: wind- or fossil-based.

In terms of GWP, the main driver has been found to be the WTT phase for both the baselines. Also, in the case of the EMPOWER demonstrators the most impactful phase is the WTT phase in almost all the demonstrator scenarios. Instead, for the BEV demonstrator with wind-based electricity, the raw material acquisition phase has been found to be the main driver accounting for 57 % of the overall impact. This outcome demonstrates that the more the decarbonization strategy is effective and the GWP reduced, the more the impact shifts towards vehicle production and raw material supply. Lastly, compared to the DIE-LH, the scenario in which hydrogen is produced by means of AE with a fossil-based electricity mix is the worst, nevertheless it allows for a GWP reduction of 39 % against DIE-LH. The scenario in which hydrogen produced by means of AE with wind-based electricity resulted to be the least impactful allowing for a GWP reduction of 80 %. Compared to the DIE-R, the BEV scenario with wind-based electricity resulted as the least impactful scenario in terms of GWP allowing for a GWP reduction of 89 %.

The comprehensive LCA results (assessing not only GWP but also other impact categories) have shown that the WTT phase emerged as the most impacting phase in almost all impact categories. Conversely, the acquisition of raw materials emerged as the most impacting phase in the mineral and metal resource use category. This highlights the need for efficient circular economy strategies coupled with decarbonization strategies. In this study the vehicle and the Li-ion battery packs have assumed to be recycled and credits are given as a benefit for the avoided production of virgin materials. In fact, recycling Li-ion battery packs may have significant benefits in other impact categories than GWP among which use of mineral and metal resources

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

in FCEV and BEV scenarios. The benefits are mainly due to the avoided production of virgin copper, cobalt, and nickel. Also, recycling the vehicle has benefits in terms of circularity.

Moving from the vehicle level to the part level, ad-hoc LCA models have been developed for the Li-ion batteries, FC system, and hydrogen tanks. It is worth noting that, for the FCEV demonstrator, the catalyst has been found to be the most environmentally impactful component in the FC system, primarily attributed to the presence of platinum. This is attributable to the significant energy consumption and GHG emissions associated with platinum production, encompassing mining, processing, and refining stages. For the BEV demonstrator, the GWP of the Li-ion battery has been found to be predominantly influenced by raw material extraction and manufacturing phases. This is mainly due to battery cell production, with cobalt sulphate and nickel sulphate being the primary contributors, alongside electricity consumption and lithium carbonate. The EoL stage, particularly the recycling process, marginally affected the climate change impact. However, notable environmental burdens are observed in ozone depletion, ionizing radiation, photochemical ozone formation, terrestrial eutrophication, land use, and fossil resource consumption during the recycling process. This is chiefly attributed to diesel utilization as fuel in the recycling process, thereby indirectly impacting diesel production.

For the TCO, the two baselines were evaluated across their entire life cycles, from purchase to EoL, which represents the resale phase for fleet operators. Key determinants influencing the economic viability of the demonstrators, notably purchase cost and energy carrier cost, were identified, collectively constituting over 50% of the overall economic evaluation. While certain costs, such as driver expenses, remained constant and beyond immediate control, the focus remained on controllable aspects, particularly the subsystems of the demonstrators. Through targeted efforts aimed at mass production and consequent cost reductions in components like battery packs, fuel cell stacks, and hydrogen tanks, efforts aim to achieve TCO parity in 2030 and a TCO reduction over the 2030s. Furthermore, the critical importance of the energy carrier, lying beyond direct manufacturer control, was emphasized. Thus, a comprehensive exploration of various scenarios is essential to equip policymakers with the insights necessary for guiding the freight transport sector towards decarbonization, aligning with the overarching goals of the EMPOWER project.

Further improvements and scenarios are under study for development during WP7 and deployment in deliverable D7.1. Among the main aspects, great efforts are in place from both POLITO and IVG to increase the primary data coverage in the LCA and TCO results of both the baselines and the EMPOWER demonstrators. All the models developed during the preliminary LCA and TCO assessment will be fine-tuned during the project according to the future advancements in the demonstrator design.

For both LCA and TCO, further scenarios are under considerations to better depict the future 2029 situation. Instead, for what concerns the lifetime, 700,000 km has been assumed as the vehicle lifetime for all the vehicles under study, accordingly EURO 7 draft [84]. Further scenarios are under consideration to evaluate the use of the annual mileage multiplied by the actual operation years based on the most likely replacement cycles adopted by fleet operators in the freight transport sector (i.e., truck ages can vary widely across different countries and company sizes). So that, for the regional baseline truck, an annual mileage of 73,000 km/year and, for the long-haul baseline truck, an annual mileage of 108,000 km/year will be considered, based on the standard mileages reported in table 4 of Annex I of the CO_2 regulation for HDV [48].

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Bibliography

[1] «COMMUNICATION FROM THE COMMISSION - The European Green Deal». 30 marzo 2022. [Online]. Disponibile su: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document1

[2] «Greenhouse gas emissions from transport in Europe, EEA, 2021», feb. 2022. [Online]. Disponibile su: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport

[3] «ACEA_preliminary_CO2_baseline_heavy-duty_vehicles.pdf».

[4] «ACEA-report-vehicles-in-use-europe-2022.pdf». Consultato: 23 maggio 2024. [Online]. Disponibile su: https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf

[5] «Regulation - 2017/2400 - EN - EUR-Lex». Consultato: 23 maggio 2024. [Online]. Disponibile su: https://eur-lex.europa.eu/eli/reg/2017/2400/oj

[6] JRC European Commission, «ILCD handbook - General guide for life cycle assessment - Detailed guidance». marzo 2010.

[7] M. A. Curran, «Life-Cycle Assessment», in *Encyclopedia of Ecology*, Elsevier, 2016, pp. 359–366. doi: 10.1016/B978-0-12-409548-9.09700-1.

[8] S. Sun e M. Ertz, «Life cycle assessment and Monte Carlo simulation to evaluate the environmental impact of promoting LNG vehicles», *MethodsX*, vol. 7, p. 101046, 2020, doi: 10.1016/j.mex.2020.101046.

[9] British Standards Institution, «BS EN ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework». 2006.

[10] BSI - British Standards Institution, «BS EN ISO 14044:2006+A1:2018 Environmental management - Life cycle assessment - Requirements and guidelines». 2006.

[11] M. Z. Hauschild, R. K. Rosenbaum, e S. I. Olsen, A c. di, *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-56475-3.

[12] S. Ross e D. Evans, «Excluding site-specific data from the lca inventory: how this affects life cycle impact assessment», *Int. J. Life Cycle Assess.*, vol. 7, fasc. 3, pp. 141–150, mag. 2002, doi: 10.1007/BF02994048.

[13] S. Islam, S. G. Ponnambalam, e H. L. Lam, «Review on life cycle inventory: methods, examples and applications», *J. Clean. Prod.*, vol. 136, pp. 266–278, nov. 2016, doi: 10.1016/j.jclepro.2016.05.144.

[14] F. Cluzel, Y. Leroy, e B. Yannou, *Toward a structured functional unit definition framework to limit LCA results variability*. 2013.

[15] H. Ny, J. P. MacDonald, G. Broman, R. Yamamoto, e K.-H. Robért, «Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic», *J. Ind. Ecol.*, vol. 10, fasc. 1–2, pp. 61–77, 2006, doi: 10.1162/108819806775545349.

[16] S. Suh *et al.*, «System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches», *Environ. Sci. Technol.*, vol. 38, fasc. 3, pp. 657–664, feb. 2004, doi: 10.1021/es0263745.

[17] R. Frischknecht e G. Rebitzer, «The ecoinvent database system: a comprehensive web-based LCA database», *J. Clean. Prod.*, vol. 13, fasc. 13–14, pp. 1337–1343, nov. 2005, doi: 10.1016/j.jclepro.2005.05.002.

[18] M. B. Ferreira *et al.*, «Eco-efficiency of the differential ratio change in a heavy-duty vehicle and implications for the automotive industry», *Sustain. Prod. Consum.*, vol. 21, pp. 145–155, gen. 2020, doi: 10.1016/j.spc.2019.12.005.

[19] S. Hanesch, F. Schöpp, L. Göllner-Völker, e L. Schebek, «Life Cycle Assessment of an emerging overhead line hybrid truck in short-haul pilot operation», *J. Clean. Prod.*, vol. 338, p. 130600, mar. 2022, doi: 10.1016/j.jclepro.2022.130600.

[20] A. E. M. Van Den Oever, D. Costa, e M. Messagie, «Prospective life cycle assessment of alternatively fueled heavy-duty trucks», *Appl. Energy*, vol. 336, p. 120834, apr. 2023, doi: 10.1016/j.apenergy.2023.120834.

[21] R. Sacchi, C. Bauer, e B. L. Cox, «Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles», *Environ. Sci. Technol.*, vol. 55, fasc. 8, pp. 5224–5235, apr. 2021, doi: 10.1021/acs.est.0c07773.

[22] S. Tahir e M. Hussain, «LIFE CYCLE ASSESSMENT OF HYDROGEN FUELCELL-BASED COMMERCIAL & HEAVY-DUTY VEHICLES», 2020.

[23] K. Wang, V. Gordillo Zavaleta, Y. Li, S. M. Sarathy, e A. F. N. Abdul-Manan, «Life-cycle CO2 mitigation of China's class-8 heavy-duty trucks requires hybrid strategies», *One Earth*, vol. 5, fasc. 6, pp. 709–723, giu. 2022, doi: 10.1016/j.oneear.2022.05.013.

[24] S. Wolff, M. Seidenfus, K. Gordon, S. Álvarez, S. Kalt, e M. Lienkamp, «Scalable Life-Cycle Inventory for Heavy-Duty Vehicle Production», *Sustainability*, vol. 12, fasc. 13, p. 5396, lug. 2020, doi: 10.3390/su12135396.

[25] N. R. Baral *et al.*, «Biomass feedstock transport using fuel cell and battery electric trucks improves lifecycle metrics of biofuel sustainability and economy», *J. Clean. Prod.*, vol. 279, p. 123593, gen. 2021, doi: 10.1016/j.jclepro.2020.123593.

[26] S. Bhardwaj e H. Mostofi, «Technical and Business Aspects of Battery Electric Trucks—A Systematic Review», *Future Transp.*, vol. 2, fasc. 2, pp. 382–401, apr. 2022, doi: 10.3390/futuretransp2020021.

[27] J. Cooper e P. Balcombe, «Life cycle environmental impacts of natural gas drivetrains used in road freighting», *Procedia CIRP*, vol. 80, pp. 334–339, 2019, doi: 10.1016/j.procir.2019.01.070.

[28] M. El Hannach, P. Ahmadi, L. Guzman, S. Pickup, e E. Kjeang, «Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks», *Int. J. Hydrog. Energy*, vol. 44, fasc. 16, pp. 8575–8584, mar. 2019, doi: 10.1016/j.ijhydene.2019.02.027.

[29] Z. Lyu, D. Pons, e Y. Zhang, «Emissions and Total Cost of Ownership for Diesel and Battery Electric Freight Pickup and Delivery Trucks in New Zealand: Implications for Transition», *Sustainability*, vol. 15, fasc. 10, p. 7902, mag. 2023, doi: 10.3390/su15107902.

[30] M. S. Middela *et al.*, «Complete LCA of battery electric and conventional fuel vehicles for freight trips», *Transp. Res. Part Transp. Environ.*, vol. 110, p. 103398, set. 2022, doi: 10.1016/j.trd.2022.103398.

[31] J. L. Osorio-Tejada, E. Llera-Sastresa, e S. Scarpellini, «Environmental assessment of road freight transport services beyond the tank-to-wheels analysis based on LCA», *Environ. Dev. Sustain.*, vol. 26, fasc. 1, pp. 421–451, ott. 2022, doi: 10.1007/s10668-022-02715-7.

[32] M. Jahangir Samet, H. Liimatainen, e O. P. R. Van Vliet, «GHG emission reduction potential of road freight transport by using battery electric trucks in Finland and Switzerland», *Appl. Energy*, vol. 347, p. 121361, ott. 2023, doi: 10.1016/j.apenergy.2023.121361.

[33] G. K. Booto, K. Aamodt Espegren, e R. Hancke, «Comparative life cycle assessment of heavy-duty drivetrains: A Norwegian study case», *Transp. Res. Part Transp. Environ.*, vol. 95, p. 102836, giu. 2021, doi: 10.1016/j.trd.2021.102836.

[34] A. Alonso-Villar, B. Davíðsdóttir, H. Stefánsson, E. I. Ásgeirsson, e R. Kristjánsson, «Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland», *J. Clean. Prod.*, vol. 369, p. 133249, ott. 2022, doi: 10.1016/j.jclepro.2022.133249.

[35] V. Balboa-Espinoza, J. Segura-Salazar, C. Hunt, D. Aitken, e L. Campos, «Comparative life cycle assessment of battery-electric and diesel underground mining trucks», *J. Clean. Prod.*, vol. 425, p. 139056, nov. 2023, doi: 10.1016/j.jclepro.2023.139056.

[36] T. Lommahadthai, «INTEGRATED LIFE-CYCLE ECONOMIC AND ENVIRONMENTAL IMPACT ASSESSMENT FOR ROAD FREIGHT TRANSPORT: A CASE STUDY FOR ELECTRIC, COMPRESSED NATURAL GAS, AND DIESEL TRUCKS».

[37] A. T. Ramshankar, A. G. Desai, J. A. De La Villarmois, e J. F. Bozeman Iii, «Sustainability analysis of overhead cable line powered freight trucks: a life cycle impact and techno-economic assessment toward transport electrification», *Environ. Res. Infrastruct. Sustain.*, vol. 3, fasc. 1, p. 015010, mar. 2023, doi: 10.1088/2634-4505/acc273.

[38] R. Arch, «AUTHORS Technical Evaluation and Life Cycle Assessment of Long-haul Heavy Duty Vehicles in 2050», *RESE ARCH*.

[39] K. J. Palm, «An Evaluation of Sustainable Designs for Trucks -a life cycle analysis».

[40] Dora Burul, David Algesten, «Life cycle assessment of distribution vehicles Battery electric vs diesel driven», Industrial report.

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

[41] Nikolas Hill, Sofia Amaral, Samantha Morgan-Price, Tom Nokes, Judith Bates (Ricardo Energy & Environment), Hinrich Helms, Horst Fehrenbach, Kirsten Biemann, Nabil Abdalla, Julius Jöhrens (ifeu), Eloise Cotton, Lizzie German, Anisha Harris, Sabine Ziem-Milojevic, Sebastien Haye, Chris Sim and Ausilio Bauen (E4tech)., «Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA», Final Report for the European Commission, DG Climate Action, lug. 2020.

[42] L. Ellram, «Total Cost of Ownership: An Analysis Approach for Purchasing», *Int. J. Phys. Distrib. Logist. Manag.*, vol. 25, pp. 4–23, ott. 1995, doi: 10.1108/09600039510099928.

[43] L. M. Ellram, «Total Cost of Ownership», in *Handbuch Industrielles Beschaffungsmanagement: Internationale Konzepte — Innovative Instrumente — Aktuelle Praxisbeispiele*, D. Hahn e L. Kaufmann, A c. di, Wiesbaden: Gabler Verlag, 2002, pp. 659–671. doi: 10.1007/978-3-663-01582-6_34.

[44] S. Parkhi, *Total Cost of Ownership (TCO)*. 2014.

[45] H. Basma, «Fuel-cell hydrogen long-haul trucks in Europe: A total cost of ownership analysis». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://theicct.org/publication/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22/

[46] C. Rout, H. Li, V. Dupont, e Z. Wadud, «A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel», *Heliyon*, vol. 8, fasc. 12, p. e12417, dic. 2022, doi: 10.1016/j.heliyon.2022.e12417.

[47] V. Shrotriya, «TIME VALUE OF MONEY -THE CONCEPT AND ITS UTILITY», mar. 2019.

[48] European Union, *Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC*. Consultato: 9 gennaio 2024. [Online]. Disponibile su: https://eur-lex.europa.eu/eli/reg/2019/1242/oj

[49] *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/1242 as regards strengthening the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, and repealing Regulation (EU) 2018/956*. 2023. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:88:FIN

[50] A. Alonso-Villar, B. Davíðsdóttir, H. Stefánsson, E. I. Ásgeirsson, e R. Kristjánsson, «Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland», *J. Clean. Prod.*, vol. 369, p. 133249, ott. 2022, doi: 10.1016/j.jclepro.2022.133249.

[51] O. Delgado, F. Rodriguez, e R. Muncrief, *Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020–2030 timeframe*. 2017.

[52] J. Dunn, A. Kendall, e M. Slattery, «Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts», *Resour. Conserv. Recycl.*, vol. 185, p. 106488, ott. 2022, doi: 10.1016/j.resconrec.2022.106488.

[53] N. Liu, F. Xie, Z. Lin, e M. Jin, «Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks», *Mitig. Adapt. Strateg. Glob. Change*, vol. 25, fasc. 3, pp. 477–493, mar. 2020, doi: 10.1007/s11027-019-09896-z.

[54] Z. Lyu, D. Pons, e Y. Zhang, «Emissions and Total Cost of Ownership for Diesel and Battery Electric Freight Pickup and Delivery Trucks in New Zealand: Implications for Transition», *Sustainability*, vol. 15, fasc. 10, Art. fasc. 10, gen. 2023, doi: 10.3390/su15107902.

[55] X. Ma, Q. Wang, S. Xiong, e Y. Yuan, «Application of fuel cell and alternative fuel for the decarbonization of China’s road freight sector towards carbon neutral», *Int. J. Hydrog. Energy*, vol. 49, pp. 263–275, gen. 2024, doi: 10.1016/j.ijhydene.2023.08.067.

[56] I. Mareev, J. Becker, e D. U. Sauer, «Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation», *Energies*, vol. 11, fasc. 1, Art. fasc. 1, gen. 2018, doi: 10.3390/en11010055.

[57] L. Schloter, «Empirical analysis of the depreciation of electric vehicles compared to gasoline vehicles», *Transp. Policy*, vol. 126, pp. 268–279, set. 2022, doi: 10.1016/j.tranpol.2022.07.021.

[58] A. Burke, «Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040», 2020, doi: 10.7922/G2H993FJ.

[59] A. Burke, M. Miller, A. Sinha, e L. Fulton, «Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results», ago. 2022, Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://escholarship.org/uc/item/1g89p8dn

[60] A. F. Burke, J. Zhao, M. R. Miller, A. Sinha, e L. M. Fulton, «Projections of the costs of medium- and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues», *Energy Sustain. Dev.*, vol. 77, p. 101343, dic. 2023, doi: 10.1016/j.esd.2023.101343.

[61] Earl, «Analysis of long haul battery electric trucks in EU», ago. 2018. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://www.transportenvironment.org/discover/analysis-long-haul-battery-electric-trucks-eu/

[62] A. Phadke, A. Khandekar, N. Abhyankar, D. Wooley, e D. Rajagopal, «Why Regional and Long-Haul Trucks are Primed for Electrification Now», None, 1834571, ark:/13030/qt3kj8s12f, mar. 2021. doi: 10.2172/1834571.

[63] C. Hunter, M. Penev, E. Reznicek, J. Lustbader, A. Birky, e C. Zhang, «Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks», 2021, doi: 10.2172/1821615.

[64] T. A. Gunawan e R. F. D. Monaghan, «Techno-econo-environmental comparisons of zero- and low-emission heavy-duty trucks», *Appl. Energy*, vol. 308, p. 118327, feb. 2022, doi: 10.1016/j.apenergy.2021.118327.

[65] H. Basma, «A total cost of ownership comparison of truck decarbonization pathways in Europe», International Council on Clean Transportation. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/

[66] «Euro 7 standard proposal - European Commission». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://single-market-economy.ec.europa.eu/publications/euro-7-standard-proposal_en

[67] E. Ravigné e P. Da Costa, «Economic and environmental performances of natural gas for heavy trucks: A case study on the French automotive industry supply chain», *Energy Policy*, vol. 149, p. 112019, feb. 2021, doi: 10.1016/j.enpol.2020.112019.

[68] R. Vijayagopal e A. Rousseau, «Electric Truck Economic Feasibility Analysis», *World Electr. Veh. J.*, vol. 12, fasc. 2, Art. fasc. 2, giu. 2021, doi: 10.3390/wevj12020075.

[69] «Comparison of Medium- and Heavy-Duty Technologies in California». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://www.atlasevhub.com/resource/comparison-of-medium-and-heavy-duty-technologies-in-california/

[70] A. Burnham *et al.*, «Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains», Argonne National Lab. (ANL), Argonne, IL (United States), ANL/ESD-21/4, apr. 2021. doi: 10.2172/1780970.

[71] California Air Resources Board, «Advanced Clean Trucks Regulation | California Air Resources Board». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://ww2.arb.ca.gov/rulemaking/2019/advancedcleantrucks

[72] «Estimating the infrastructure needs and costs for the launch of zero-emission trucks». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://theicct.org/publication/estimating-the-infrastructure-needs-and-costs-for-the-launch-of-zero-emission-trucks/

[73] B. Sharpe e H. Basma, *A Meta-Study of Purchase Costs for Zero-Emission trucks*. 2022.

[74] Kuhn et al, «E-Truck Virtual Teardown Study», 11 giugno 2021.

[75] M. Tanco, L. Cat, e S. Garat, «A break-even analysis for battery electric trucks in Latin America», *J. Clean. Prod.*, vol. 228, pp. 1354–1367, ago. 2019, doi: 10.1016/j.jclepro.2019.04.168.

[76] X. Zhang, Z. Lin, C. Crawford, e S. Li, «Techno-economic comparison of electrification for heavy-duty trucks in China by 2040», *Transp. Res. Part Transp. Environ.*, vol. 102, p. 103152, gen. 2022, doi: 10.1016/j.trd.2021.103152.

[77] H. Basma, «Fuel cell electric tractor-trailers: Technology overview and fuel economy». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/

This project has received funding from the European Union’s HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

[78] B. Noll, S. del Val, T. S. Schmidt, e B. Steffen, «Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe», *Appl. Energy*, vol. 306, p. 118079, gen. 2022, doi: 10.1016/j.apenergy.2021.118079.

[79] A. Estrada Poggio, J. Balest, A. Zubaryeva, e W. Sparber, «Monitored data and social perceptions analysis of battery electric and hydrogen fuelled buses in urban and suburban areas», *J. Energy Storage*, vol. 72, p. 108411, nov. 2023, doi: 10.1016/j.est.2023.108411.

[80] H. Basma, «Total cost of ownership for tractor-trailers in Europe: Battery electric versus diesel», ICCT, 2019. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://theicct.org/publication/total-cost-of-ownership-for-tractor-trailers-in-europe-battery-electric-versus-diesel/

[81] UNECE, *UN GTR No.22 (In-vehicle Battery Durability for Electrified Vehicles) | UNECE*. Consultato: 9 gennaio 2024. [Online]. Disponibile su: https://unece.org/transport/documents/2022/04/standards/un-gtr-no22-vehicle-battery-durability-electrified-vehicles

[82] «UNECE to develop battery durability requirements for electric heavy-duty vehicles | UNECE». Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://unece.org/sustainable-development/press/unece-develop-battery-durability-requirements-electric-heavy-duty

[83] *Council Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic*. 2019. Consultato: 22 maggio 2024. [Online]. Disponibile su: http://data.europa.eu/eli/dir/1996/53/2019-08-14/eng

[84] «Euro 7 standard proposal_COM(2022) 586 ANNEX - Annex to the COM(2022) 586 Proposal for a regulation». Consultato: 13 maggio 2024. [Online]. Disponibile su: https://single-market-economy.ec.europa.eu/document/download/4c18e42e-96a4-4391-8813-0ec4d777d1bf_en?filename=COM_2022_586_F1_ANNEX_EN_V9_P1_2333970.PDF

[85] «EPD UN CPC 49112 & 49113, Environdec.pdf».

[86] M. Miotti, J. Hofer, e C. Bauer, «Integrated environmental and economic assessment of current and future fuel cell vehicles», *Int. J. Life Cycle Assess.*, vol. 22, fasc. 1, pp. 94–110, gen. 2017, doi: 10.1007/s11367-015-0986-4.

[87] British Standards Institute Staff, *ISO 14040. Environmental management. Life cycle assessment. Principles and framework*. Place of publication not identified: Bsi, 2006.

[88] British Standards Institute Staff, *ISO 14044. Environmental management. Life cycle assessment. Requirements and guidelines*, Withdrawn. 2018.

[89] «FC_Guidance_Document.pdf».

[90] S. M. Ali, I. I. I. Alkhatib, A. AlHajaj, e L. F. Vega, «How sustainable and profitable are large-scale hydrogen production plants from CH4 and H2S?», *J. Clean. Prod.*, vol. 428, p. 139475, nov. 2023, doi: 10.1016/j.jclepro.2023.139475.

[91] S. Krishnan, B. Corona, G. J. Kramer, M. Junginger, e V. Koning, «Prospective LCA of alkaline and PEM electrolyser systems», *Int. J. Hydrog. Energy*, vol. 55, pp. 26–41, feb. 2024, doi: 10.1016/j.ijhydene.2023.10.192.

[92] CE Delft *et al.*, *Handbook on the external costs of transport: version 2019 – 1.1*. LU: Publications Office of the European Union, 2020. Consultato: 16 gennaio 2024. [Online]. Disponibile su: https://data.europa.eu/doi/10.2832/51388

[93] European Commission. Directorate General for Mobility and Transport. *et al.*, *Transport taxes and charges in Europe: an overview study of economic internalisation measures applied in Europe.* LU: Publications Office, 2019. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://data.europa.eu/doi/10.2832/416737

[94] Comité national routier, «Enquête CNR longue distance 2019 | COMITE NATIONAL ROUTIER», 2019. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/node/266

[95] Comité national routier, «The UK road freight transport sector | COMITE NATIONAL ROUTIER», 2019. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/uk-road-freight-transport-sector

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

[96] Comité national routier, «The Netherlands - The Dutch road freight transport sector - 2019 | COMITE NATIONAL ROUTIER», 2019. Consultato: 15 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/netherlands-dutch-road-freight-transport-sector-2019

[97] Comité national routier, «The Polish road freight transport sector - 2019 | COMITE NATIONAL ROUTIER», 2019. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/polish-road-freight-transport-sector-2019

[98] Comité national routier, «The Spanish road freight transport sector - 2020 | COMITE NATIONAL ROUTIER», 2020. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/spanish-road-freight-transport-sector-2020

[99] Comité national routier, «The German road freight transport sector - 2021 | COMITE NATIONAL ROUTIER», 2021. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/german-road-freight-transport-sector-2021

[100] Comité national routier, «The Italian road freight transport sector - 2021 | COMITE NATIONAL ROUTIER», 2021. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/en/italian-road-freight-transport-sector-2021

[101] Comité national routier, «Enquête CNR longue distance 2022 | COMITE NATIONAL ROUTIER», 2022. Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://www.cnr.fr/enquete-cnr-longue-distance-2022

[102] Q. Wang, M. Marshall, e F. Lewis, «Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks», feb. 2022. [Online]. Disponibile su: https://escholarship.org/content/qt36c08395/qt36c08395_noSplash_589098e470b036b3010eae00f3b7b618.pdf?t=r6zwjb

[103] «Weekly Oil Bulletin». Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en

[104] «Statistics | Eurostat». Consultato: 18 gennaio 2024. [Online]. Disponibile su: https://ec.europa.eu/eurostat/databrowser/product/page/nrg_pc_205

[105] *Council Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the Community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic*, vol. 235. 1996. Consultato: 18 gennaio 2024. [Online]. Disponibile su: http://data.europa.eu/eli/dir/1996/53/oj/eng

This project has received funding from the European Union's HORIZON EUROPE research and innovation programme under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Acknowledgment

European Union's HORIZON EUROPE research and innovation program

This project has received funding from the European Union's HORIZON EUROPE research and innovation program under grant agreement No. 101096028. The content of this publication is the sole responsibility of the Consortium partners listed herein and does not necessarily represent the view of the European Commission or its services.

Project Partners:

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Participant No*	Participant short name	Participant organisation name	Country
1 Coordinator	**AIT**	AIT Austrian Institute of Technology GmbH	AT
2	**IVECO**	IVECO SPA	IT
3	**FPT**	FPT Industrial SPA	IT
4	**IFPEN**	IFP Énergies nouvelles	FR
5	**POLITO**	Politecnico di Torino	IT
6	**LT**	Lead Tech SRL	IT
7	**VIL**	Villinger GmbH	AT
8	**CID**	Fundación CIDETEC	ES
9	**CTE**	CT Engineering GmbH	AT
10	**GLO**	Gruber Logistics S.p.A.	IT
11	**BRE**	BREMBO SPA	IT
12	**IIT**	Istituto per Innovazioni Tecnologiche Bolzano S.c.a.r.l.	IT
13	**ALFI**	Air Liquide	FR
14	**FMF**	FPT Motorenforschung AG	CH