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Life Cycle Assessment of zero-emission heavy-duty vehicles - Analysis of the ESCALATE project pilots

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Executive Summary

For assessing the life cycle sustainability of the new technologies developed in the Escalate project, ecological indicators are analyzed. The usage of the vehicles in on-road tests offers access to specific real-world data for the covered use cases. As different drive train technologies are covered, a comparison of the different technologies on a vehicle-to-vehicle basis is necessary. Based on emissions and resource consumption modelling, we discuss first results for the carbon footprint of the project's pilot vehicles and corresponding reference vehicles based on simulation data. The focus of the evaluation is on the well-to-wheel analysis in combination with the geographical locations of the test routes. In addition, we show how to extend the vehicle-based analysis to a fleet level and how such results can support decisions on further political measures.

Keywords: Heavy Duty electric Vehicles & Busses, Fuel Cell Systems, Life Cycle Analysis, Environmental Impact, Climate Change

1 Introduction

To reduce the environmental impact of the transport sector, the EU aims at reducing CO_2 emissions from heavy-duty vehicles (HDV) along with other measures. The current target is a 90% reduction of the HDV CO_2 emissions by 2040, with intermediate goals of 45% by 2030 and 65% by 2035. A key measure here is to increase the electrification of the truck sector. To avoid the shift of emissions into other sectors, the assessment of the entire life cycle of such new vehicles including manufacturing and electricity production during the use phase is necessary. The EU funded ESCALATE project aims at exploring the life cycle and social impacts of cutting-edge zero-emission vehicle (ZEV) technologies, including HDVs powered by batteries, fuel cells, and range extenders. The project focusses on developing highly scalable and modular eco-designed electric powertrain components and flexible platforms for battery, fuel cell and range extender trucks (up to 44t), complemented by data-driven algorithms, tools and interfaces, and bridge the physical and digital worlds (5 modular digital twins) to enable EU manufacturers and logistics companies to evaluate cost-effective solutions [1].

Through the examination of pilot vehicles tested in different European locations, ESCALATE will provide crucial insights into the environmental and social implications of these emerging technologies. The here presented initial step of the environmental assessment is based on quantifying the potential burdens on a vehicle level using detailed vehicle configurations and simulation data. The second step will incorporate real-world operational data to refine the analysis. In a third step, the analysis will be extended to future technology scenarios and applied to an EU fleet level.

The integration of the simulation and real-world data helps identifying potential environmental hotspots, particularly related to vehicle usage patterns and key components such as batteries, fuel cells (FCs) or photovoltaic systems (PVs) in some cases. Such findings underscore the importance of considering component-specific impacts and usage scenarios in future sustainable vehicle concepts. In this paper, we outline the methodology and first results of this life cycle assessment (LCA).

2 Methodology

2.1 Life Cycle Assessment of the ESCALAT pilot vehicles

The comprehensive LCA aims at evaluating the environmental impacts of the pilot HDVs of the project compared to reference HDVs. This includes conventional diesel vehicles, but also zero emission technologies available on the market. The focus of our current analysis is on the optimization of pilot technologies and comparative assessments across different countries where the use cases take place. The project leverages standardized LCA methodologies to ensure consistency, reliability, and comparability of results across various technologies and operational scenarios.

The system boundaries of the study cover the entire vehicle life cycle, from raw material extraction to manufacturing, operation, maintenance, and end-of-life disposal. This includes the evaluation of different battery types as well as fuel cells. A holistic approach is employed to capture both upstream and downstream processes, ensuring a full assessment of greenhouse gas emissions, resource consumption, and waste generation.

The focus of this paper is the analysis of a reference diesel truck in comparison to two fuel-cell electric vehicles (FCEV) operated in Finland, Turkey and France and one refrigerator solar battery truck (BEV) operated in the UK and Germany (Table 1) which represent 3 pilot applications out of 5 of the entire ESCALATE project. As the project is still in progress, we present first results and discuss main influencing factors for the vehicle production, such as battery chemistry and fuel cell production. For the refrigerator BEV, the contribution of the solar panels to its energy supply will be shown. A full analysis of the vehicle production will be conducted at a later stage of the ESCALATE project.

In the vehicle use stage, the project evaluates different drivetrain technologies on a vehicle-to-vehicle basis by employing real-world data collected from the on-road tests. Particularly, the analysis focuses on how geographical variations in the test routes influence the sustainability indicators of the pilot vehicles. Furthermore, one of the added values of this study lies in the inclusion of real-world industrial demonstrators. Their participation enables the LCA methodology to incorporate operational insights and real fleet data, which strengthens the reliability and applicability of the conclusions for heavy-duty commercial ZEV deployment. Different operational conditions and regional specificities make it necessary to design tailored LCA studies, especially when it comes to HDVs operating under high payload and long-distance routes. In this context, ESCALATE includes high-impact demonstrators such as Primafrio, whose network of long-haul and regional temperature-controlled transport across Europe contributes critical insights. The company’s operations encompass more than 6,000 connected vehicles, over 5.2 million tons transported annually, and an average fleet age of just 1.4 years, providing a robust data foundation for assessing ZEVs under real commercial stress and operational intensity.

Table 1: Characteristics of the pilot vehicles considered in this paper [1-3]

	FC-REEV	FCEV	Refrigerator BEV
Powertrain technology	Fuel cell range extender electric truck (SISU)	Fuel cell electric truck (BMC)	Battery-electric refrigeration truck (ELECTRA)
Countries of operation	Finland	Regional: Turkey Long haul: France	Regional: UK Long haul: Germany
Routes	Regional: Helsinki (50 km) Long haul: Jyväskylä - Helsinki (525 km)	Regional: Gebze – Izmir (500 km) Long haul: Grenoble – Munich (800 km)	Regional: Dundee – Southampton (760 km) Long haul: Flensburg – Karlsruhe (Wörth am Rhein) (780 km)
Operational and capacity targets	Improving in delivery times and operational costs, particularly in winter conditions.	Demonstration of the regional mission (500km daily) with a mobile hydrogen filling station and cross-border route of 800 km on a single refill range.	Based on the proven Electra platform, consisting of 3 axles (centre e-axle), with refrigerated body and electric tail lift; 800 km without recharging, and a daily duty cycle of 500 km in real world conditions.
Energy and environmental performance	Reducing carbon emissions compared to conventional truck and trailer combinations, esp. considering performance in harsh weather.	Improving energy efficiency by 5 % at minimum.	Approx 1000 kWh batteries, photo-voltaic cells on the entire roof area.

In the current stage of the project, first results of the well-to-wheel emissions of the pilots have been analyzed. This allows an initial assessment of the level of emissions compared to the reference vehicles. The system boundaries are chosen specifically for each vehicle (Figure 1) with a focus on the drive system for vehicle production and the different energy requirements and supply chains according to the geographical areas of use. All calculations are based on the situation today, with an outlook on technological changes and the resulting emission profiles up to 2050 being provided in a more advanced status of the project.

Preliminary calculations on reference vehicles with different drive technologies as well as numerous literature sources have shown that although the use phase has the greatest influence, the lithium-ion batteries and the fuel cell as additional drive components are associated with high environmental impacts during production. Changing the batteries and other components during the use phase therefore also results in significant emissions. In addition, the origin of the energy for vehicle operation plays a decisive role. This analysis is based on the electricity mix of the respective countries for the operation of the vehicles. In the case of hydrogen, it is assumed that it is produced from renewable sources, which is in line with the objectives of the project. The ecoinvent 3.9 database is used as the data source for the use of the background processes and energy generation. Further sensitivity analyses on various energy sources, battery types etc. will be carried out during the project. A central aspect here will be the comparison of the real data collected with the simulation data from various project partners [2,3] used in this article. The OpenLCA software was used for the calculation, as it enables simple exchange between different project partners.

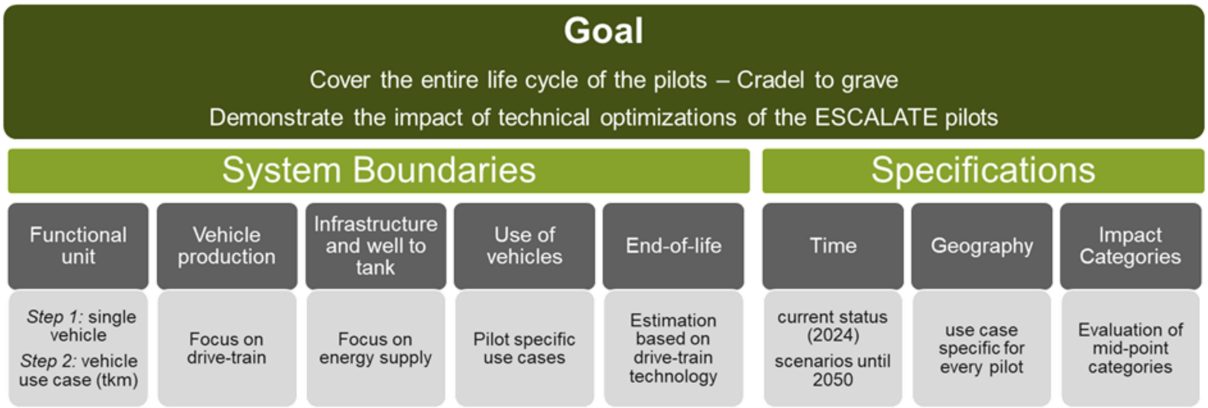

Figure 1: Overview of goals and scope of the analysis

2.2 Fleet Analysis

This section addresses the methodological transition of LCA from a single-product to a fleet-based approach. Such an adaptation appears necessary from a policy perspective to better account for fleet-wide induced emissions (both country-specific and European) and to effectively evaluate the impacts of existing and future interventions in heavy-duty vehicle transportation systems. In this context, Figure 2 presents the rationale for calculating fleet emissions.

Using the fleet operation over a year as the functional unit, the fleet is treated as a product with an annual lifetime, encompassing all life cycle stages. Manufacturing emissions are calculated for new registrations, in-use emissions for both new registrations and the existing fleet, and end-of-life emissions for deregistered vehicles. Fleet activity data are sourced from the SIBYL model [4], while Tank-to-Wheel (TtW) emissions are calculated using COPERT [5]. Upstream emissions (Well-to-Tank, WtT), manufacturing, and maintenance emissions are obtained from secondary databases and reports (e.g., JEC, ecoinvent, GREET).

Total fleet-induced emissions for a target year (2022) are calculated by aggregating all life cycle stages. Projections are subsequently made for the following years, extending up to 2050.

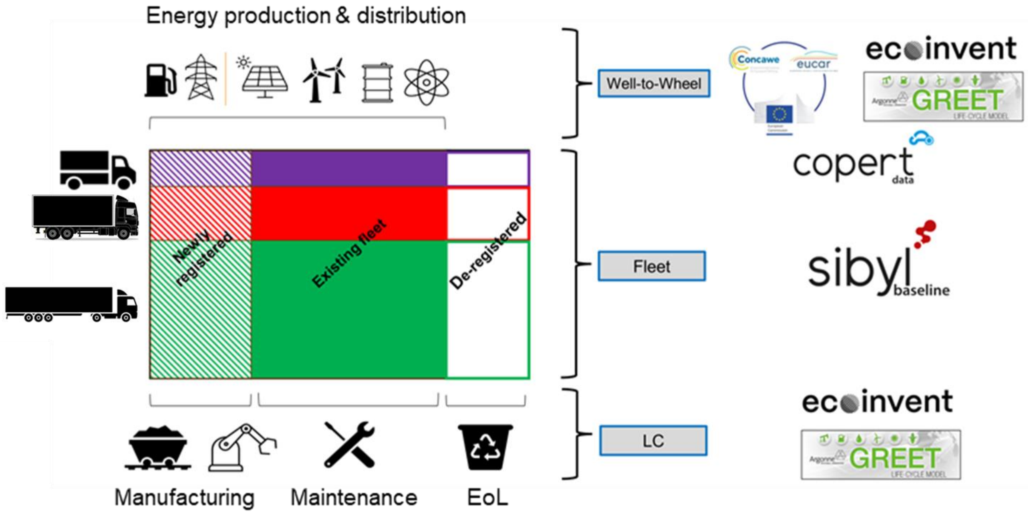

Figure 2: Fleet level LCA: Adding lifecycle-related impacts on fleet-based environmental assessments

To illustrate the significance of the fleet-based approach, scenarios are developed to quantify overall emissions from road transport in Europe as electrified vehicles replace conventional ones. Figure 3 depicts a realistic transition of the heavy-duty market towards electrified solutions by 2050. In this scenario, new sales of conventional diesel trucks are gradually reduced starting in 2035 and are largely phased out by 2050, replaced primarily by BEVs and FCEVs. This transition to electrified solutions is reflected in the total fleet composition, with electrified vehicles becoming predominant from 2045 onwards.

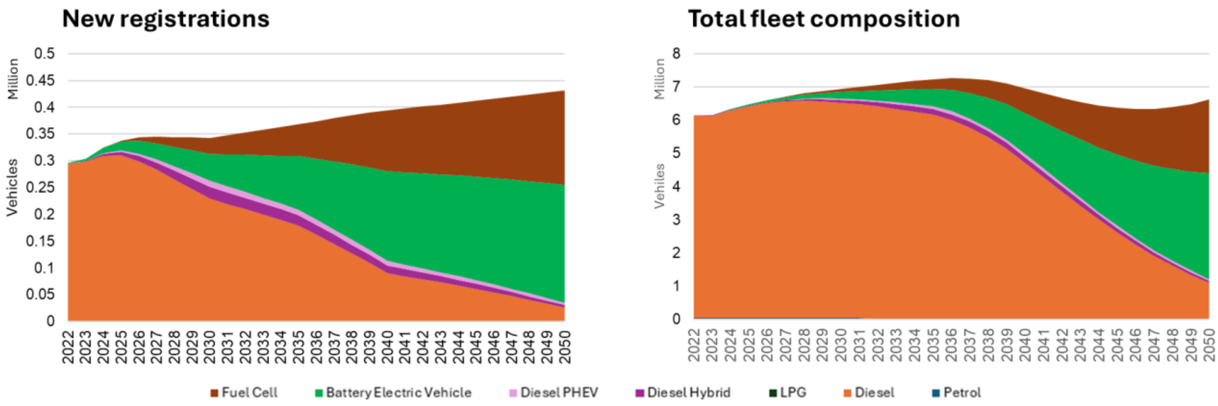

Figure 3: New registrations and fleet composition derived from SIBYL

3 Results

3.1 Preliminary Analysis of Key Components

3.1.1 LCA of Batteries

As lithium-ion batteries play an increasingly pivotal role in the electrification of transportation, it is imperative to assess their environmental sustainability, particularly in the context of heavy-duty vehicles, which have high energy demands and operate under rigorous conditions. This section provides a comprehensive environmental assessment of two widely utilized lithium-ion battery chemistries: Nickel Manganese Cobalt (NMC), and Lithium Titanate Oxide (LTO). These chemistries are deployed across four pilots aimed at evaluating electric battery performance in local, regional, and long-haul transport scenarios. Specifically, Pilots 1 and 2 focus on the use of LTO batteries, while Pilots 3 and 4 employ NMC batteries.

NMC batteries are frequently chosen for their superior energy density, which makes them particularly suitable for long-distance and high-performance transportation applications. However, this enhanced performance is accompanied by significant environmental impacts. The production phase of NMC batteries represents the most environmentally impactful segment of their life cycle, primarily due to the intensive extraction, refinement, and processing of critical raw materials. The cathode materials, predominantly nickel sulfate and cobalt sulfate, contribute significantly to these impacts [6]. Their production entails energy-intensive processes and is associated with air and water pollution, toxic byproducts, and, in the case of cobalt, ethical concerns related to mining practices. Additionally, the use of N-methyl-2-pyrrolidone, NMP, a toxic solvent in cathode manufacturing, further intensifies the ecological and human health implications [7]. The anode component, typically composed of graphite along with a copper current collector, also contributes to the battery's overall environmental footprint. The extraction and processing of copper are resource-intensive, leading to considerable energy consumption, emissions, and pollution. In summary, the material preparation stage, especially for the cathode, exhibits the most notable environmental impact [8].

On the other hand, LTO batteries, although exhibiting lower energy density, provide distinct benefits regarding safety, thermal stability, and cycle longevity, making them especially appropriate for local transport applications, as evidenced by Pilots 1 and 2. Yet, the environmental profile of LTO batteries also requires careful consideration [9]. Similar to NMC, the production phase is the most impactful, with the environmental burden mainly concentrated in the anode production. This anode, typically formed from lithium titanate, is derived from titanium dioxide and lithium oxide. The production of titanium dioxide is associated with extensive chemical use, significant mining waste, and environmental pollution. Lithium oxide extraction, whether through hard rock mining or brine processes, poses environmental challenges such as water scarcity, carbon emissions, and ecosystem disruption [9]. Both types of batteries underscore a critical insight: the environmental sustainability of battery technologies is profoundly influenced by upstream supply chains and the sourcing of raw materials.

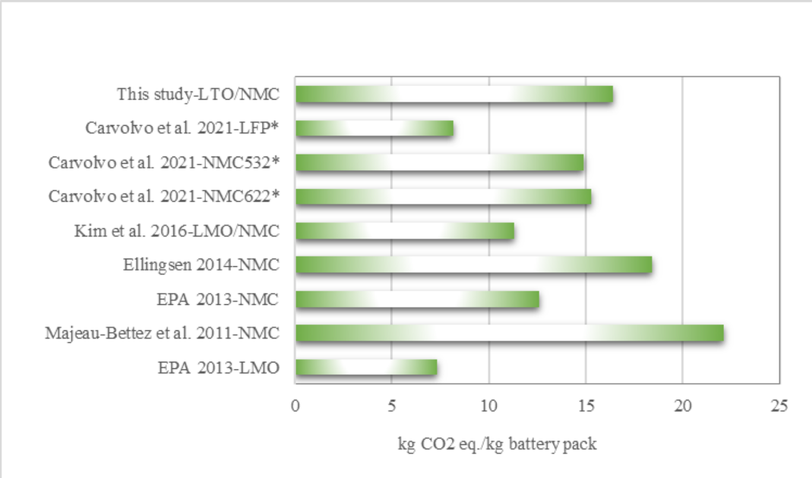

Figure 4: Comparison of cradle-to-gate GHG emissions per kg of battery pack/cell* [10-14]

Figure 4 compares the carbon footprint (kg CO_2 eq/kg battery pack) across different studies and battery chemistries. The present study reports an LTO/NMC configuration based on a literature-based assessment, rather than real-world operational data from the actual system. For this preliminary evaluation, LTO and NMC values were derived from different published sources and combined at the battery pack level (per kg basis). The resulting carbon footprint is approximately 18 kg CO_2 eq/kg battery pack, comparable to that of NMC622 and NMC532 chemistries reported by Carvolvo et al. (2021) [10]. In contrast, batteries based on LFP and LMO chemistries demonstrate significantly lower carbon emissions, highlighting the influence of material selection on the overall environmental impact. Earlier assessments, such as those by Ellingsen (2014) [14] and Majeau-Bettez et al. (2011) [12], show relatively higher emission values, possibly reflecting differences in manufacturing energy mix, material efficiencies, and methodological assumptions over time. Overall, the results emphasize that battery chemistry, data sources, and production processes are critical drivers of the life cycle carbon footprint of battery systems.

In conclusion, although NMC and LTO batteries cater to differing performance needs within heavy-duty transport, their environmental impacts are fundamentally rooted in the materials and processes involved in their production. NMC batteries face challenges primarily related to the environmental consequences of their cathodes, whereas LTO batteries contend with the environmental costs associated with their anode materials. In the future, strategies such as responsible material sourcing, enhanced recycling rates, and the adoption of cleaner manufacturing practices will be essential for reducing the life cycle impacts of battery technologies, particularly as their utilization grows across various transportation sectors.

3.1.2 Impact of Fuel Cells

The preliminary analysis also extends to fuel cells as another hotspot in vehicle production, where the membrane electrode assembly (MEA) components were identified as having the most significant environmental impact, primarily in terms of resource depletion and global warming potential. Advancements in catalyst and membrane technologies, along with effective recycling and end-of-life management strategies, are identified as key factors for mitigating the environmental footprint impacts of fuel cells. Data show that the source of platinum used has a significant influence on the environmental impact of fuel cell production. Usai et al. (2021) [15] assumes a secondary share of 50 to 75 %. However, this range appears to be an optimistic forecast in view of the current platinum secondary share of approx. 24-30 % [16,17].

In the case of heavy-duty transport, experiences of operators like Primafrio show that real-world operational variables—such as high annual mileage (>200,000 km per unit), continuous refrigeration load, and payload maximization—significantly influence the LCA outcomes. These parameters amplify energy consumption and therefore increase the sensitivity of Global Warming Potential (GWP) to energy source and vehicle efficiency. As a result, scenarios involving BEVs or FCEVs show wider variation in impact depending on infrastructure availability and energy origin (i.e., electricity vs. H_2 production location and method).

3.2 Well-to-wheel (WtW) Assessment of the Pilot Vehicles

3.2.1 WtW Analysis of the FC-REEV, FCEV and refrigerator BEV

The initial findings indicate an investigation of reference vehicle technology relative to two fuel-cell electric vehicles and one solar battery truck with refrigeration capabilities. The total emissions for well-to-wheel (WW) in the reference scenario (40t) were 1.1 kg CO_2/km. The overall WtW emissions and contributions are outlined in Figure 5. The FC-REEV has shown lower total well-to-wheel (WtW) emissions, but fuel cell electric vehicles (FCEVs) used for long trips and regional travel have much lower overall WtW emissions compared to the reference scenario or FC-REEV. This is mostly attributable to the removal of the battery for primary propulsion, which was contributing additional emissions alongside the propulsion system for the fuel cell. The BEV demonstrates the lowest emissions among all drivetrains, with the reference scenario emitting merely 0.48 kg CO_2/km for regional applications and 0.52 kg CO_2/km for long-haul applications.

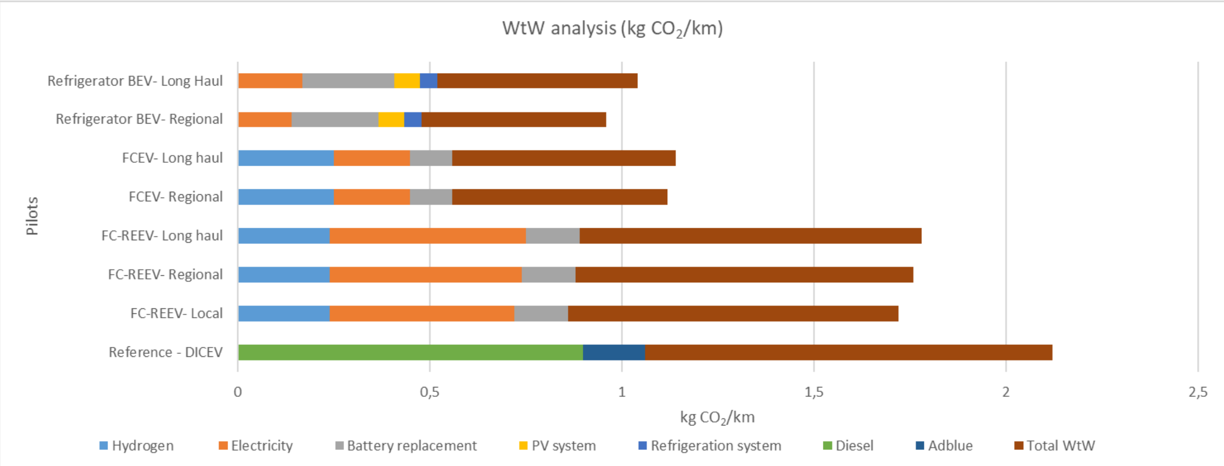

Figure 5: WtW analysis of pilots – Fuel cell range extender electric vehicle (FC-REEV), fuel cell electric vehicle (FCEV), and refrigerator battery electric vehicle

However, the emissions from FCEVs, FC-REEV, and BEV could decrease if the electricity used for hydrogen production or battery charging is derived from clean energy sources. This study investigated the standard electricity mix in Germany. In the subsequent phase of the study, we intend to evaluate the green mix for hydrogen and energy generation over the next period of years. We anticipate a reduction in electricity for charging or hydrogen production if it comes from renewable sources.

3.2.2 Analysis of the Refrigerator BEV and Impacts of PV and Cooling System

The refrigerator BEV of this study is equipped with photovoltaic (PV) panels. For the given use cases in Germany and UK (Table 2, Figure 6), an analysis of the energetic benefits of these panels has been calculated. For the PV roof, driving direction is not an issue since the PV panel has a tilt of 0º. Thus, PV output is independent of driving start and end time. The actual demonstrator will be built with PV only on the trailers' roofs. For the PV side panels, driving direction and time affect PV output since the panels are vertically placed. Additionally, PVs on the side of the truck were simulated for comparison purposes and to portray their added benefit. The cycles were built using an in-house Route Profile Generator (RPG) modelled on MATLAB.

Table 2: Driving cycles for UK and Germany

	UK Cycle	German Cycle
Average Speed [km/h]	81	81
Total Distance [km]	760	780
Total Duration (without afternoon parking) [hr]	11.2	11.8
Break between driving Duration [hr]	1.5	1.5
Driving Start Time	3:00	3:00
Driving End Time	14:00	14:15
Afternoon Parking Vehicle Direction	South	South

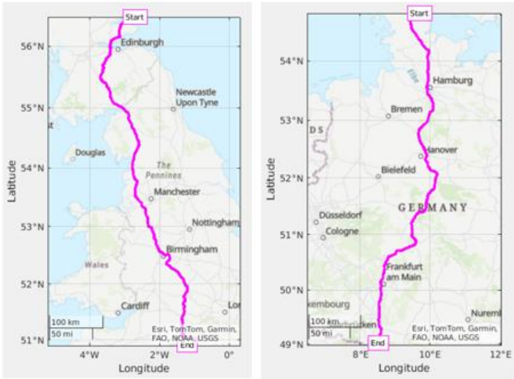

Figure 6: Driving cycles for UK and Germany

The PV panels [18] used have the following specifications:

- PV efficiency: 16.4%
- Weight: < 3 kg/m^2
- PV technology: lightweight Copper Indium Gallium Selenide (CIGS).
- Power electronics modelled: MPPT and DCDC controller
- PV Models were modelled on MATLAB Simulink.

An in-house simulation tool called SIC (Solar Irradiance Calculator) was developed on MATLAB to calculate the year-round solar irradiance on the different truck trailer zones (roof, left side, right side) while considering changes in the vehicle driving directions. The model uses irradiance and ambient temperature data from NSRDB [19] for horizontal PV panels and adapts them for different PV panel's directions and tilts. SIC simulations are joined with an in-house MATLAB RSG (Random Shading Generator) tool to simulate shading and include its effects on PV energy generation.

The following assumptions were considered:

- 1 drive per day
- Number of driving days per month:

1. Germany [20,21]: no driving on Sundays year-round, bank holidays, and on Saturdays in July and August.
2. UK [22]: no restrictions exist, only rules for drivers and not for trucks on the road.

Table 3 Results for PV energy production [kWh] and PV mileage [km]

	Germany	UK
Peak monthly PV production [kWh]	Peak in June. Roof-only variant: ~400 Roof+Sides variant: ~950	Peak in April, May, July. Roof-only variant: ~ 280 Roof+Sides variant: ~720
Yearly cumulative output [kWh]	Roof-only variant:~1640 Roof+Sides variant: ~ 3970	Roof-only variant:~1550 Roof+Sides variant: ~ 4100
*PV mileage [km/year]	Roof-only variant: ~1170 Roof+Sides variant: ~2850	Roof-only variant: ~1110 Roof+Sides variant: ~2950

**Considering ELECTRA truck consumption of 140 kWh/100km*

Notice that the sides' contributions increase total PV output compared to roof alone variant by 2.4 times for Germany and 2.6 times for the UK. PV panels tilted to almost vertically receive more diffuse light than direct sunlight. The UK has a cloudier climate than Germany, meaning it gets a higher share of diffuse solar radiation throughout the year. Since vertical panels capture diffuse light more effectively, they tend to perform better under such conditions. Therefore, in this specific tilt scenario, the UK's diffuse-light advantage can lead to a higher annual PV output than in Germany, despite Germany generally receiving more total solar radiation (Figure7).

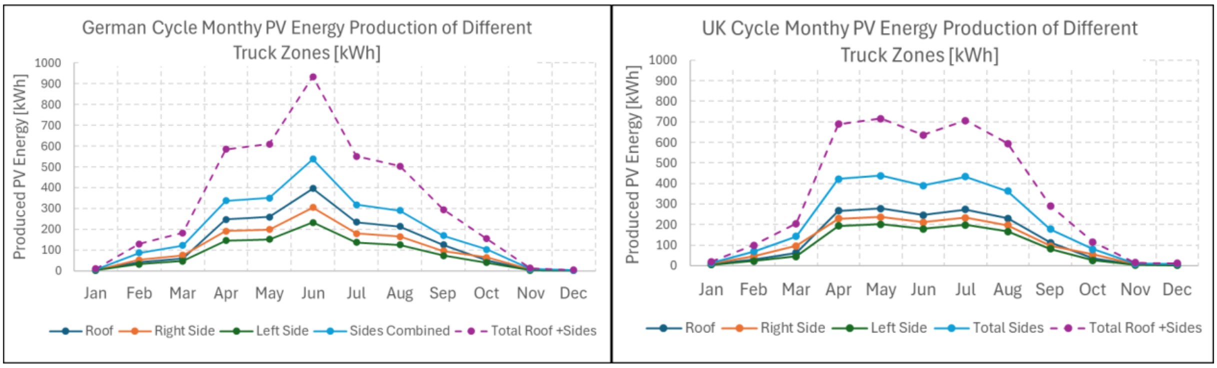

Figure 7: Monthly PV energy production of different truck zones for Germany and the UK

To compare the refrigeration requirements with PV production, the worst-case scenario was assumed for the refrigeration simulation. This includes various door openings (8) with extended durations (5 to 20 min) and heavy cargo masses (up to 5525 kg). Three different controller strategies were designed and compared:

1. Standard MPC controller, which gently cools the compartment down prior to every door-opening.
2. Constrained MPC controller, designed to be suitable for sensitive goods, which aggressively cools the compartment down prior to a door-opening.
3. Economic MPC controller, designed for non-sensitive goods, which either turns the refrigeration unit off completely or balances reduction and increase in motor speed.

Since the ELECTRA demonstrator is planned to be with only PV roof, the following results use PV production data with the roof-only variant. Among the three, the constrained MPC achieves the shortest PV coverage period due to its aggressive cooling behavior (Figure 8). The standard and economic MPCs perform similarly in terms of energy use, but the economic version is more efficient, consuming about 21% less energy. For the UK, the fulfillment of refrigeration requirements by PV production is more challenging, where only the economic MPC can be covered in some months (Table 4). This could be due to the higher refrigeration requirements from the more frequent driving cycles per month in combination with the UK's lower overall PV production compared to Germany.

Table 4: Months where PV production satisfies Refrigeration requirements for Germany and UK

	Germany	UK
Standard MPC	May till August	-
Constrained MPC	Only in June	-
Economic MPC	April till August	April till July

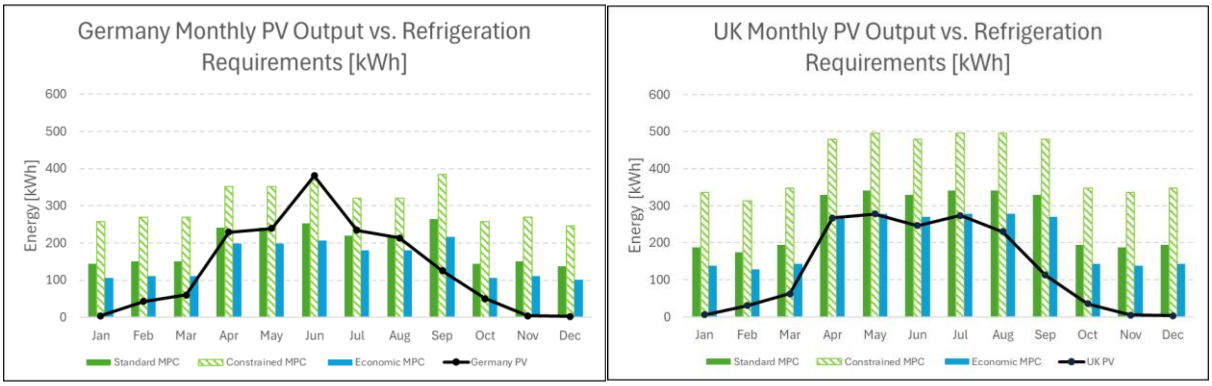

Figure 8: Monthly PV outputs compared to refrigeration requirements [kWh] for Germany and the UK

3.4 Fleet analysis

The fleet element in our method generates data related to the entire vehicular activity in Europe. Figure 9 presents the fleet LCA CO_2 results (right panel) from 2022 to 2050 in Europe under the electrification scenario previously described. As already mentioned, LCA CO_2 provides the complete picture of the fleet footprint, including manufacturing, energy production (WtT) and energy use (TtW). The TtW consideration is also separately provided in the left panel of Figure 9 to highlight the difference gap that is introduced in total emissions when considering the LCA impacts. Emissions are reduced through electrification between 2022 and 2050, even when assessed from an LCA perspective. Considering TtW emissions alone results in a 79% reduction (2022 vs. 2050), while the LCA approach shows a 67% reduction.

Comparing the two approaches, their divergence becomes evident and is influenced by fleet composition. The gap is at its minimum, 25%, when internal combustion engine vehicles dominate the fleet (i.e., in 2022), as the majority of their CO_2 emissions occur directly during on-road operation (TtW). In this case, the TtW method provides a reasonable approximation without significant loss of accuracy. However, the gap increases to 53% when electrified powertrains dominate the fleet (i.e., by 2050), underscoring the necessity of LCA for accurate assessment under such conditions. This is expected, as the CO_2 impacts of electrified vehicles are primarily associated with upstream processes, such as energy production (WtT) and manufacturing, which are only captured through LCA.

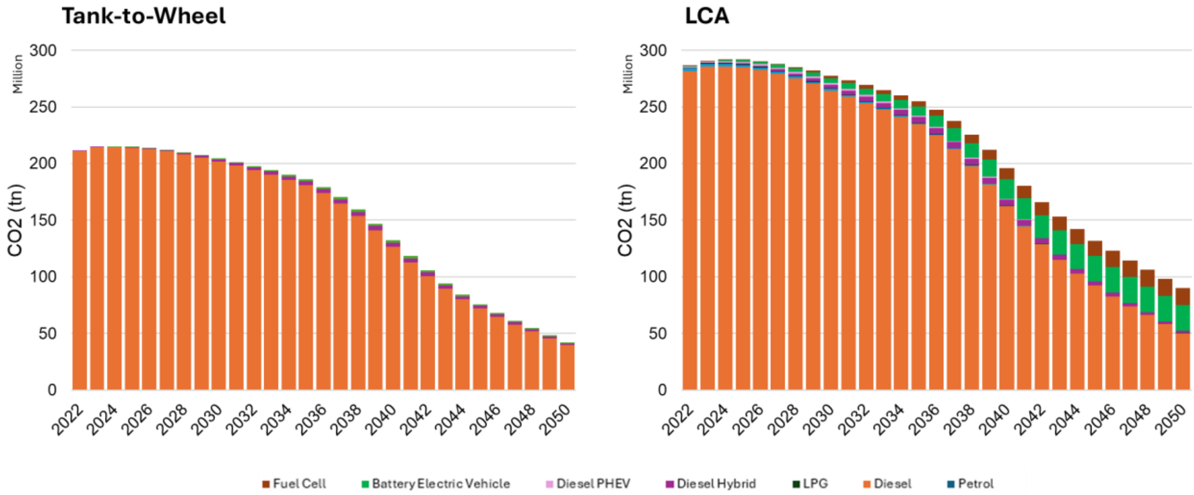

Figure 9: TtW and LCA CO_2 emissions for the fleet

The major share of emissions attributed to TtW is reduced as fossil-fueled trucks are gradually phased out of the market. The WtT emissions of BEVs do not fully substitute the TtW emissions of ICEVs, due to the gradual decarbonization of the electricity mix and the higher efficiency of electrified powertrains. Manufacturing emissions from BEVs become more influential in the early years, driven by increased demand for new vehicles and batteries. However, this influence stabilizes in later years, as improvements in battery production footprints offset the continued rise in demand (Figure 10).

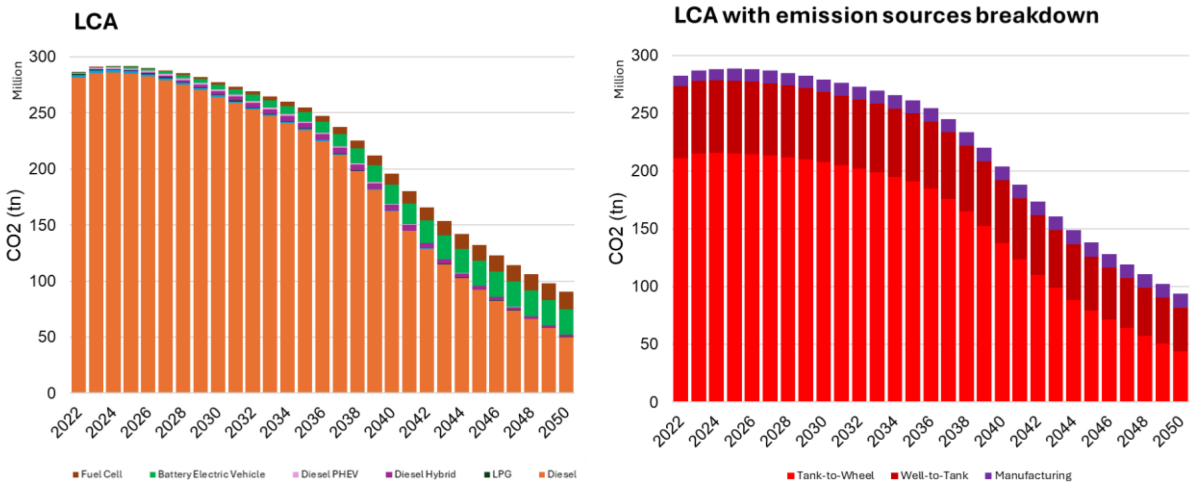

Figure 10: LCA emissions with emission sources breakdown

4 Conclusion and Outlook

While current results are preliminary, they suggest significant potential reductions in life cycle greenhouse gas emissions and pave the way for future recommendations on urban infrastructure adaptations to accommodate these technologies better. This study will integrate data from various project partners, providing valuable insights at vehicle and fleet levels. The ultimate goal is to guide the development of more sustainable electric vehicles and fuel cell technologies through informed technical optimizations, original data for the pilot vehicles and global environmental impact assessments. From a practical standpoint, large-scale fleet operators involved in the project offer critical input to LCA modelling due to their ability to supply accurate real-life TCO and energy consumption data over extended missions. This expected empirical evidence will reinforce the integration of LCA findings with techno-economic assessments and supports the transition from theoretical modelling to policy-relevant and investment-ready outputs. Furthermore, LCA is not only a tool for assessing environmental performance but also a critical component for understanding the long-term economic viability (TCO) of emerging technologies in freight transport. For large logistics operators, that are also part of the project, early technological decisions—whether in favor of battery electric, hydrogen fuel cell, or advanced biofuels—carry not only environmental implications but substantial economic risk. A misaligned choice can lead to significant financial losses, operational disruptions, or failure to meet regulatory requirements, potentially compromising the resilience of supply chains for essential goods across Europe and globally. Therefore, achieving alignment between regulation, technology readiness, infrastructure deployment, and both short- and long-term economic outlook is essential to avoid systemic inefficiencies and ensure a truly sustainable and secure decarbonization pathway for the transport sector.

The findings are expected to aid in the development of tailored policies and infrastructure adaptations that support the deployment of sustainable heavy-duty transport solutions. Moreover, the ESCALATE project's pilot results highlight the effectiveness of innovative modular vehicle designs. These designs facilitate the reuse and extension of vehicle parts and components' life, significantly reducing environmental footprints compared to traditional internal combustion engine vehicles.

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6 References

[1] ESCALATE (2025). Powering European Union Net Zero Future by Escalating Zero Emission HDVs and Logistic Intelligence. Project homepage, Demos & Pilots description. https://www.escalate-eu.com/problem-statement-vision/ (accessed on 25 April 2025)

[2] Pihlatie, M,, Ranta, M., Tota, S.S., Utku, Ü., Hartavi, A.E., et al. (2025). Baseline Assessment of ESCALATE Zero Emission Long-Haul Truck Demonstrations Regarding Total Cost of Ownership. EVS 38, June 15-18, 2025, Göteborg, Sweden.

[3] Skeel, E., Hentunen, A., Pihlatie, M., Vepsäläinen, J., Ranta, M., Singh, P., Tota, S.S. (2025). Energy Management for a Fuel Cell Plug-in Hybrid Heavy-duty Vehicle. EVS 38, June 15-18, 2025, Göteborg, Sweden.

[4] Joint Research Center (JRC). Vehicle Stock, Air Pollutants, and GHG Projection Policy Evaluation Tool. Available online: https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-sibyl/ (accessed on 24 April 2025)

[5] Joint Research Center (JRC). Computer Model to Calculate Emissions from Road Traffic. Available online: https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-copert/ (accessed on 24 April 2025)

[6] Popien, J. L., Thies, C., Barke, A., & Spengler, T. S. (2023). Comparative sustainability assessment of lithium-

ion, lithium-sulfur, and all-solid-state traction batteries. International Journal of Life Cycle Assessment, 28(4), 462–477. https://doi.org/10.1007/s11367-023-02134-4
[7] Barke, A., Thies, C., Popien, J. L., Melo, S. P., Cerdas, F., Herrmann, C., & Spengler, T. S. (2021). Life cycle sustainability assessment of potential battery systems for electric aircraft. Procedia CIRP, 98, 660–665. https://doi.org/10.1016/j.procir.2021.01.171
[8] Sun, X., Luo, X., Zhang, Z., Meng, F., & Yang, J. (2020). Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. Journal of Cleaner Production, 273. https://doi.org/10.1016/j.jclepro.2020.123006
[9] da Silva Lima, L., Wu, J., Cadena, E., Groombridge, A. S., & Dewulf, J. (2023). Towards environmentally sustainable battery anode materials: Life cycle assessment of mixed niobium oxide (XNOTM) and lithium-titanium-oxide (LTO). Sustainable Materials and Technologies, 37. https://doi.org/10.1016/j.susmat.2023.e00654
[10] Carvalho, M. L., Temporelli, A., & Girardi, P. (2021). Life cycle assessment of stationary storage systems within the Italian electric network. *Energies*, *14*(8), 2047.
[11] Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., & Lee, J. (2016). Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. *Environmental science & technology*, *50*(14), 7715-7722.
[12] Majeau-Bettez, G., Hawkins, T. R., & Strømman, A. H. (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental science & technology*, *45*(10), 4548-4554.
[13] U.S. EPA Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles; EPA 744-R-12- 001; 2013.
[14] Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H. (2014). Life cycle assessment of a lithium-ion battery vehicle pack. Journal of Industrial Ecology, 18(1), 113-124.
[15] Usai, L., Hung, C. R., Vásquez, F., Windsheimer, M., Burheim, O. S., Strømman, A. H.: Life cycle assessment of fuel cell systems for light duty vehicles, current state-of-the-art and future impacts. In: Journal of Cleaner Production 280 (2021)
[16] Schmidt, Michael: Rohstoffrisikobewertung - Platingruppenmetalle: Platin, Palladium, Rhodium. Datenstand: Dezember 2014. Berlin: DERA, 2015 (DERA Rohstoffinformationen 26)
[17] Cowley, Alison: Pgm market report: May 2021.
[18] BIPVco. (n.d.). *Product Specification: Flextron CIGS Solar PV Modules*. BiPVco -The Building Integrated Photovoltaic Company. https://bipvco.com/wp-content/uploads/2024/11/Flextron-CIGS-Specification-2024.pdf
[19] NSRDB. (n.d.). *National Solar Radiation Database*. https://nsrdb.nrel.gov/
[20] Eurowag. (2023, November 21). Rules for Truck Drivers in Germany. *Eurowag: Fuel Cards & Solutions for Transport Companies*. https://www.eurowag.com/blog/rules-for-truck-drivers-in-germany
[21] MaxxsTrans. (n.d.). *Factsheet Container Road Transportation Germany*. https://www.maxxstrans.com/galleries/36/741/factsheet-container-road-transportation-germany.pdf
[22] EP Training. (2024). New rules for lorry drivers in the UK: The 2024 changes. *eptraining.co.uk*. https://eptraining.co.uk/news/article/new-rules-for-lorry-drivers/

7 Presenter Biography

Simone Ehrenberger leads the 'Environment and Transformation' group at the Institute of Vehicle Concepts at the German Aerospace Center (DLR). With more than 15 years of professional experience in research and development, she is a specialist in technology assessment and market analysis of vehicles. Her research focuses on the ecological evaluation of vehicles and the analysis of future vehicle markets. In addition, she represents Germany at international level in working groups of the International Energy Agency's (IEA) Technology Initiative for Hybrid and Electric Vehicles (IA-HEV), including the Assessment of Environmental Effects of Electric Vehicles. Simone Ehrenberger studied geoecology at the Karlsruhe Institute of Technology. As part of her doctoral thesis, she focused intensively on the ecological assessment of future vehicle technologies, taking into account new materials and drive train systems