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CO_2e Life-Cycle Assessment: Twin Comparison of Battery–Electric and Diesel Heavy-Duty Tractor Units with Real-World Data

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Abstract: In 2023, the EU set the target to reduce greenhouse gas (GHG) emissions by 55% until 2030 compared to 1990. The European Transport Policy sees battery–electric vehicles as a key technology to decarbonize the transport sector, so governments support the adoption through dedicated funding programs. Battery–electric trucks hold great potential to decarbonize the transport sector, especially for high-impact, heavy-duty trucks. Theoretical life-cycle assessments (LCA) predict a lower CO_2e emission impact from battery–electric trucks compared to conventional diesel trucks. Yet, one concern repeatedly mentioned by potential users is the doubt about the ecological advantage of battery–electric vehicles. This is rooted in the problem of a much higher CO_2e impact of the lithium-ion batteries production process. As heavy-duty trucks have a much larger battery, the hypothec in the construction phase of the vehicle is significantly higher, which must be regained during the use phase. Although theoretical assessments exist, CO_2e evaluations using real-world application data are almost nonexistent, as the technology is at the very start of the adoption curve. Exemplary is the fact that there were only 72 registered battery–electric heavy-duty tractor trucks throughout the whole of Germany at the start of 2023. This paper aims to deliver one of the first real-world quantifications using operational data for the actual reduction impact of battery–electric heavy-duty trucks compared to diesel trucks. This study uses the methodology of the life-cycle assessment approach according to ISO 14040/14044 to gain a systematic and holistic technology comparison. For this LCA, the system boundaries are considered from cradle to cradle. This includes the production of raw materials and energy, the manufacturing of the trucks, the use phase, and the recycling afterward. The research objects of this study are battery–electric and diesel Volvo FM trucks, which have been in use by the German freight company Nord-Spedition GmbH since May 2023. The GREET® database is used to assess the emission impact of the material production and manufacturing process. The Volvo tractor trucks resemble a critical case, as the vehicles have a battery size of 540 kWh—around 11 times larger than a usual passenger car. The operation data is directly provided by the logistics company to observe fuel/electricity consumption. Other factors are assessed through company interviews as well as a wide literature research. Finally, a large question mark concerning total emissions lies in the cradle-to-cradle capabilities of large-scale lithium-ion batteries and the electricity grid mix. Different scenarios are being considered to assess potential disposal or recycling paths as well as different electricity grid developments and their impact on the overall balance. The findings estimate the total emissions reduction potential to range between 34% and 69%, varying with assumptions on the electricity grid transition and recycling opportunities. This study displays one of the first successful early-stage integrations of battery–electric heavy-duty trucks into the daily operation of a freight company and can be used to showcase the ecological advantage of the technology.

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1. Introduction

Heavy-duty vehicles used for long-distance transportation are one of the main contributors to the overall CO_2-equivalent (CO_2e) emissions of the transport sector. Hence, improving vehicles' environmental performance is vital to facing climate change. This global problem should be addressed in this paper through the case study of battery–electric heavy-duty vehicles in Germany. The German traffic sector accounted for 23.7% of the country's total CO_2e emissions in 2023 [1]. Around 25% of the emissions can be attributed to heavy-duty vehicles [2]. From the European perspective, around 6% of the total emissions are issued by heavy-duty vehicles alone [3]. While the reduction potential by battery–electric tractor units (BETs) is expected to become substantial, the current market penetration of BETs is currently insignificant. In 2023, only 1.9% of newly registered tractor units had an alternative power train. Of 133,882 heavy-duty vehicles with a payload capacity of 12 tons or more, only 190 or 0.14% had a battery–electric power train (KBA 2024). Although the innovation is technically ready for usage, it can be considered to still be in its infancy.

Next to battery–electricity, there are other alternative powertrain options to decarbonize heavy-duty vehicles such as hydrogen, overhead line electric, or liquified natural gas [4]. Among the availability and usability of innovations, policymakers targeting climate change assess the predicted emission reduction impact to decide which technology to support. These comparative evaluations have been conducted by different entities, such as the International Council on Clean Transportation (ICCT) or the Heidelberg Institute for Energy and Environmental Research (ifeu) [5,6]. However, these assessments had to rely on a list of theoretical assumptions.

The first integration of BETs into the operation of actual shipping companies offers to test those hypotheses with real-world data. This paper therefore aims to use operational data provided by the German shipping company Nord-Spedition GmbH & Co. KG of FM Electric and FM Diesel tractor units, manufactured by the Swedish company Volvo Trucks, to conduct a life-cycle assessment (LCA). The findings should indicate how large the CO_2e reduction in BETs in real-life applications is. Moreover, the results should be compared to the aforementioned studies relying on default data and assumptions as well as to estimate the reduction potential for the whole German traffic sector.

The ICCT study, "A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels" from 2023 assesses the life-cycle greenhouse gas (GHG) emissions of heavy-duty vehicles (HDVs) in Europe, focusing on 40-ton gross vehicle weight tractor units. Utilizing a comprehensive life-cycle assessment, the study evaluates emissions arising from vehicle production, maintenance, disposal, and fuel and electricity production and consumption. By 2030, a projected reduction of approximately 25% in fuel consumption is assumed. The vehicle cycle considers emissions from the entire value chain, emphasizing battery production emissions, which vary by global production location. Advanced battery technologies such as high-nickel NMC811 and lithium iron phosphate are anticipated to reduce GHG emissions, aided by a decarbonization of the energy grid. The fuel cycle examines well-to-tank and tank-to-wheel emissions. This study concludes that BETs can achieve significant GHG reductions due to greater energy efficiency and lower carbon intensity of electricity compared to fossil fuels. Despite initially high emissions from battery production, especially considering battery replacement, an overall life-cycle GHG reduction of at least 63% compared to diesel HDVs is noted [5].

The ifeu study, "Comparative Analysis of the Potentials of Drive Technologies for tractor units by 2030" from 2022 examines various tractor unit technologies, including diesel, battery–electric, fuel cell, and overhead line systems, with a focus on diesel and battery–electric variants. Employing emission overlays from the TREMOD model, the study assesses tractor units exceeding 26 tons, utilizing operational profiles derived from traffic data to construct emissions scenarios. Central to the study are the production and operational emissions under the assumption of a rapid decarbonization of the power grid, aligning with climate neutrality objectives by 2045. The methodology incorporates the analysis of life-cycle emissions, drawing on differential emissions factors for varied energy carriers and positing substantial CO_2 reductions resultant from advanced vehicle technologies and decarbonized energy supplies by 2030. Within the projected efficiency gains and emissions reductions by 2030, battery–electric demonstrate approximately 50% decreases in GHG emissions. Conclusively, battery–electric tractor units offer the most substantial CO_2 reduction potential, ranging from 48% to 57% relative to diesel counterparts [6].

The described studies use a lot of default data and assumptions. These results should be compared to the result of the analysis with real-world data.

2. Material and Methods

The methodology of this study involves conducting a life-cycle assessment (LCA) in accordance with the DIN EN ISO 14040:2021-02 and 14044:2021-02 standards [7,8]. These standards provide guidelines for creating LCAs, emphasizing international approaches and terminologies and were used due to their established usage and worldwide comparability and standardization. The LCA consists of four phases:

Goal and Scope Definition: This study aims to compare the environmental impacts of battery–electric (BET) and diesel heavy-duty tractor units in Germany, with a focus on global warming potential (GWP) from emissions. This study outlines its scope and data sources, notably using real-world operational data provided by the Nord-Spedition GmbH & Co. KG (addressed as "Nord-Spedition" in the following) from May 2023 to April 2024. It is necessary to mention that the environmental footprint of BETs is not limited to CO_2e alone. Other gases such as nitrogen oxides (NO_x) or sulfur oxides (SO_x) emitted by vehicles directly or indirectly impact the environment in different ways, such as soil acidification or smog formation. However, under the main objective of this study to address impacts concerning climate change, CO_2e was chosen as the target metric.

Life-Cycle Inventory (LCI): This phase involves gathering data on vehicle materials for production, energy use for operations, maintenance, and disposal materials. Real-world data provided by the running Volvo Tractor units and literature are integrated using the GREET® database, providing emissions data for various production-related processes [9]. The vehicle operation data are directly provided by the logistic company Nord-Spedition and consist of routes and energy data. Recycling scenarios are based on literature due to limited empirical data.

Life-Cycle Impact Assessment (LCIA): This study employs the impact category "Climate Change" to characterize greenhouse gas emissions in the form of CO_2e emissions in alignment with the Kyoto Protocol using the global warming potential (GWP100) from IPCC's AR6 report [10,11].

Interpretation: Results from the LCIA are analyzed, focusing on comparing BETs and diesel tractor units in terms of CO_2e. Different scenarios for Germany's electricity mix are considered to assess the environmental viability of BETs. This study concludes by comparing results with previously conducted LCA models to highlight specific findings and sustainability potentials for the German traffic sector.

3. Step 1: Goal and Scope

This section delineates the scope and parameters that underpin the research framework to define precise system boundaries. The investigation focuses on the Nord-Spedition, a medium-sized logistics company based in Schleswig-Holstein, Germany, which has supplied primary data crucial for a comparative analysis of vehicle drive typologies. Nord-Spedition's specialization in the transportation of liquids—spanning foodstuffs, animal feed, and chemicals—with 40-ton gross vehicle weight rating tractor units renders it an exemplary case study for the research objectives. This study comprises a comprehensive analysis of the company's electrified share of the fleet, consisting of three BETs, with the comparative evaluation of heavy-duty tractor units Volvo FM Electric and Volvo FM Diesel models. Notably, both tractor unit types have similar technical characteristics and are used for similar deliveries, allowing a twin comparison in the field. The vehicles' lifetime is set to 7 years, as further elaborated in the LCI step. The resulting time scope of usage is 2023 to 2029. Technical specifications of the research objects can be found in Table 1, including mass, engine, energy, and range information.

Table 1. Technical specifications of Volvo FM 4 $\times$ 2 and Volvo FM 42 Tractor Electric [12].

Model	FM 11 4 $\times$ 2	FM 42 Tractor Electric
Empty weight	Approx. 6150 kg	9920 kg
Permissible total weight	15,500 kg	18,000 kg
Permissible gross combination weight	39,000 kg	40,000 kg
Engine type	D11K410/420/430	3 electric motors
Engine power	410/420/430 PS	450-466 PS
Fuel	Diesel EN590	Electricity
Battery storage	-	450/540 kWh
Emission standard	EM-EU6	EM-ZE
Range estimation	-	300 km

The headquarter of the Nord-Spedition is located in Großenwiehe, Northern Germany, near the Danish border. This geographical location combined with the present operational range and centralized charging infrastructure at the company's headquarter confine the operation of these vehicles to long- and medium-distance shuttle routes within Northern Germany. Technical specifications for each tractor unit variant are outlined, and a thorough analysis of GHG emissions concerning production materials is provided. Particular attention is paid to the material proportions of steel and aluminum in diesel tractor units, and the pronounced GHG footprint of batteries and printed circuit boards (PCBs) in electric tractor units.

Clearly defining the boundaries of a life-cycle assessment (LCA) is essential to ensure comparability and validity of its results. Within these system boundaries, the following Figure 1 illustrates the data acquisition framework. Figure 1 provides an overview of the system boundaries and data sources.

Data sources are qualitatively assessed through color coding: primary data, indispensable for operational analysis and provided by the Nord-Spedition, is marked in green. This encompasses detailed trip analysis, route data, and complementary interview information to questions not directly addressable through literate research, such as maintenance. For materials and production, the GREET® database supplements additional data. The initial LCA phases rely on primary data from Volvo's LCA study. High-quality secondary data are coded in yellow, including literature insights and GREET® findings, while orange indicates uncertainty, especially in End-of-Life/Recycling scenarios. This study follows the cradle-to-grave; respectively, the cradle-to-cradle approach from raw material extraction to the disposal or recycling after the tractor unit's usage.

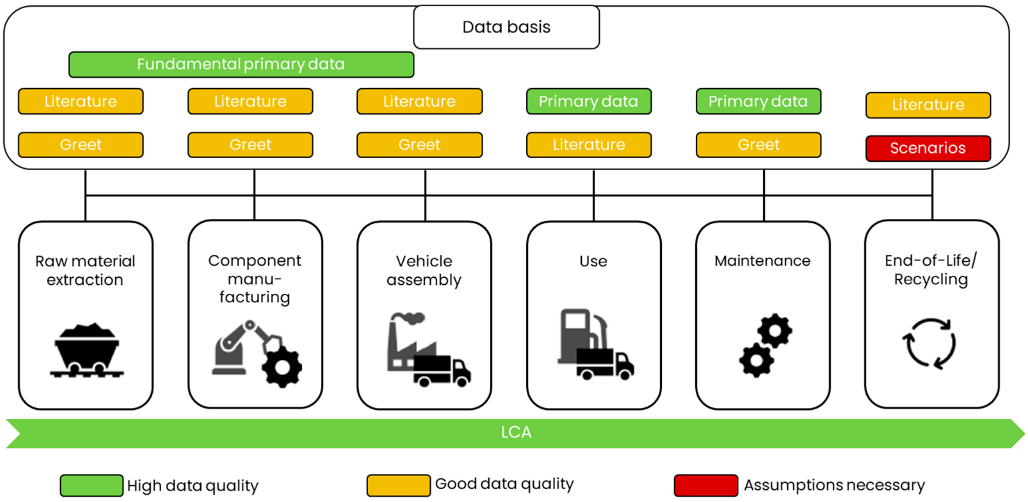

Figure 1. System boundaries and data sources (source: own illustration).

4. Step 2: Life-Cycle Inventory

The LCI and LCIA phases of the analysis have been carried out in accordance with the LCA steps shown in Figure 1. The following sections provide an overview of the information-gathering process of material and energy needs along the BET and diesel tractor unit life cycle.

4.1. LCI: Raw Material Extraction, Component Manufacturing, and Vehicle Assembly

In the process of raw material extraction and component manufacturing, the Well-to-Product (WtP) approach of the GREET® database was utilized, encompassing the entire chain from initial raw material extraction to the completion of individual components composing the tractor unit. The combination of the WtP information with data on component manufacturing and vehicle assembly resembles the entire process chain from raw material to the final product.

This integrated assessment offers a comprehensive evaluation of GHG impacts across the product life cycle, capturing synergies and interactions among process phases. The WtP assessment relies on Volvo's data regarding resource distribution in their tractor units. For the Volvo Diesel FM and FM Electric, the material weight distribution is based on the technical level closely related FMX Diesel and FMX Electric model data. The data was provided on request directly by the Volvo Group [13]. Based on the FMX model, the tractor unit's weight is calculated to 6300 kg. The composition of the material for the FM Diesel tractor is illustrated in Figure 2. Figure 3 shows the calculation of the FM Electric tractor, noting significant differences for the electric variant due to its 3000 kg battery pack, a major contributor to its higher total weight of 9920 kg. The bar charts on the right show the individual materials with their absolute mass values as well as the vehicle's total mass. The pie charts on the left show the corresponding shares of the total mass. Dominant materials for both vehicle types include steel (44% or 32% of the total vehicle mass) and cast iron (30% or 20% of the total vehicle mass).

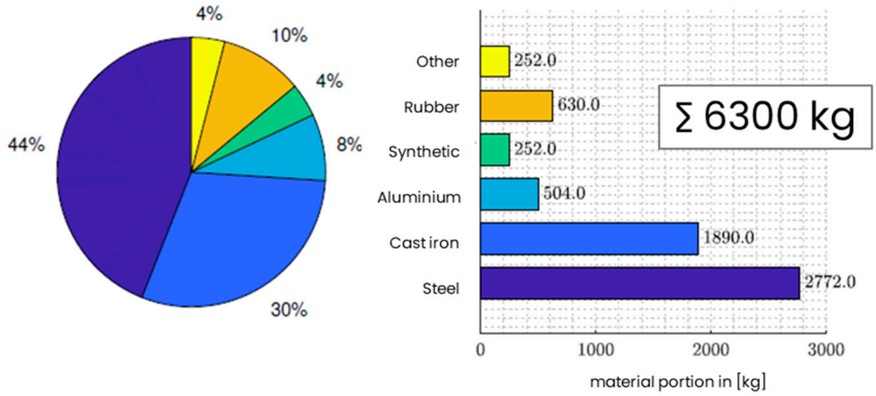

Figure 2. Resource composition of Volvo FM Diesel (based on the FMX model).

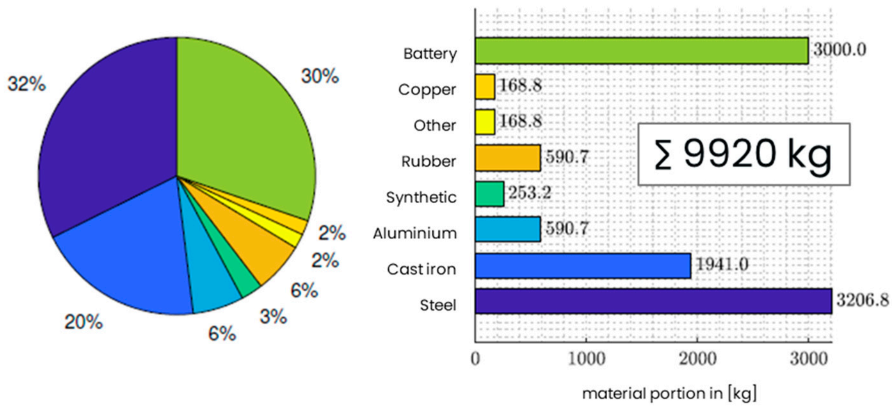

Figure 3. Resource composition of Volvo FM Electric (based on the FMX model).

Within the GREET® model, system boundaries are essential to simulate resource extraction processes. For each material, the CO_2e emission factor specified with the energy mix of its production location was gathered to calculate the overall emissions.

In the assessment of emissions related to vehicle assembly, the GREET® Part Manufacturing and Vehicle Assembly (VMA) model was employed to compute the environmental impacts involved in parts manufacturing and vehicle assembly throughout the vehicle's life cycle. This "bottom-up" approach focuses on energy consumption and CO_2e emissions and applies to conventional as well as advanced vehicles, including those with high aluminum content, hybrids, plug-in hybrids, and fully electric vehicles. A critical aspect of the VMA model is its weight-based distribution function for materials and associated processing activities, such as casting and stamping, derived from the "Generic Vehicle Life Cycle Inventory" study by the United States Council for Automotive Research. The model incorporates extensive data from literature regarding processing and factory operational data, enabling accurate modeling of numerous processes. Battery production in electric vehicles, being relatively energy-intensive, significantly contributes to energy loads in the VMA phase. A multi-stage process replicating vehicle assembly has been implemented in GREET® as the basis for analyzing vehicle manufacturing in this study.

4.2. LCI: Usage and Maintenance

In analyzing the emissions from usage and maintenance of the Volvo FM Electric and FM Diesel tractor units, operational data provided by the Nord-Spedition was utilized. For the Volvo FM Electric, data concerning fuel and energy, with key metrics including the timestamp, covered distances and energy consumption were used. These metrics allow to assess vehicle performance and energy savings potential. For the Volvo FM Diesel, additional metrics such as total diesel consumption and AdBlue® usage were analyzed, providing insights into fuel efficiency and emissions. The operational data were checked for quality using a 95%-quantile approach on data points transformed to energy consumption per 100 km driving to detect outliers. This method offers a simple and intuitive way to clean the data set, while assumptions of the specific distribution of the data are not required. Data points outside the lower and upper bounds of the interval were deleted from the data set. Analyzing the data this way, anomalies in energy consumption in October 2023 were found. Correspondence with the shipping company confirmed these findings, as one of the vehicles had to undergo minor maintenance.

The Nord-Spedition provided practical insights, noting vehicle operational lifespans of 7 years and an expected total mileage approaching one million kilometers. Maintenance routines include tire replacements, oil changes, and periodic part replacements. The average annual mileage was determined at 130,000 km for both diesel and electric vehicles. The FM Electric's energy consumption averaged 113.91 kWh per 100 km. The energy consumption in accordance with the months within a year is shown in Figure 4. Clearly visible is the characteristic correlation for battery–electric vehicles between energy consumption and warm and cold months of the year, showing the influence of the outside temperature.

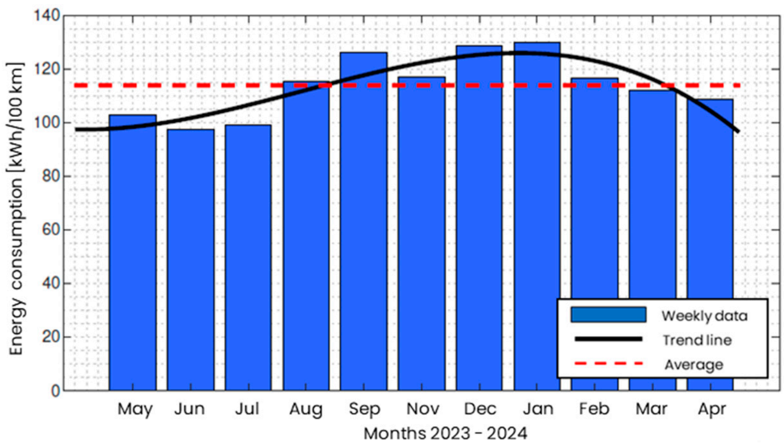

Figure 4. Average energy consumption of Volvo FM Electric over a year from 2023 to 2024.

For diesel vehicles, the average fuel consumption was 25.08 L per 100 km, with similar, yet less significant, temperature-dependent variations noted in energy use as in the electric counterpart. AdBlue® consumption patterns aligned with diesel usage, averaging an 8.32% mixture ratio. The following Figure 5 illustrates the FM Diesel's average energy profile.

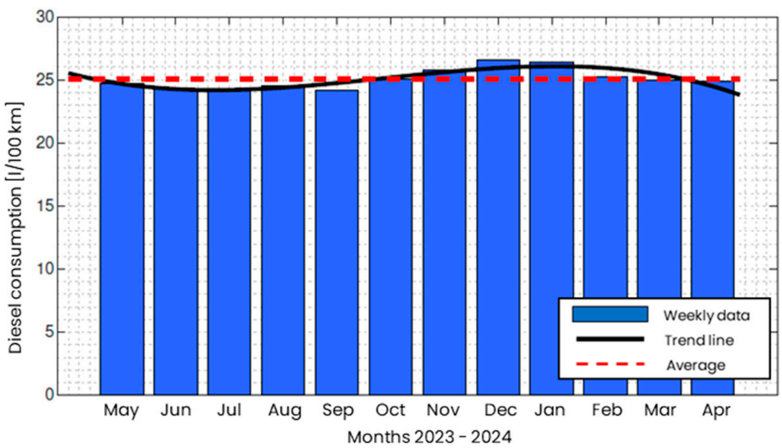

Figure 5. Average energy consumption of Volvo FM Diesel over a year from 2023 to 2024.

Maintenance and operational resources for the FM Electric emphasize tire wear, with a calculated annual replacement mass percentage reduced through retreading practices. Due to the usage context of regional to long-distance drives, a higher load on tires was resumed, resulting in a tire change every 100,000 km. The FM Diesel, lighter at 6300 kg, faces proportionally higher maintenance emissions due to additional consumables like motor oil and AdBlue®. Concerning motor oil, this study assumed an annual consumption of 33 L, a value obtained by interviewing the shipping company. Furthermore, the maintenance of certain parts was integrated. These parts consist of particle filters (every 450,000 km), air dryer cartridges (every 140,000 km), cabin air filter (every 130,000 km), belts, tensioners, transmission, and rear axle oil (all every 400,000 km).

4.3. LCI: Recycling and End-of-Life

Material recycling is pivotal for sustainability, effectively reducing new resource extraction and promoting material reuse at the end-of-life (EoL). Different recycling methods can be applied to foster the transition toward an ideal closed-loop system. These include mechanical recycling, hydrometallurgical recycling, pyrometallurgical recycling, and direct recycling [14]. Other approaches concern operational and supply chain optimization using stochastic optimization or artificial intelligence to directly integrate recycling processes in supply chain planning [15,16]. The recycling process incurs energy and resource consumption but prepares materials for reuse, granting environmental credits based on post-recycling quality and quantity. Notably, printed circuit boards, although significant for climate impacts, are often not dismantled but go through shredding, contaminating metal streams or incineration. For the FM Electric, results align similarly, prominently influenced by batteries, the primary factor affecting production and recycling impacts. Critical materials, particularly nickel, hold significant reduction potential, along with aluminum, cobalt, steel, and copper, although not all battery emissions are recoverable due to fossil-based manufacturing. Recycling assessment complexity is heightened by variable data points and recovery fractions heavily reliant on material composition, production dates, and geographic recycling conditions [17]. In addition to batteries, recovering bulk materials like steel and aluminum notably mitigate impacts, while plastic incineration remains a climate concern, where recycling could offset new production needs [18].

Despite numerous technical lifespan studies of lithium-ion batteries, real-world end-of-life studies regarding recycling or re-use of large-scale lithium-ion batteries are sparse [19,20]. Batteries potentially enter a secondary use phase rather than retirement, mainly due to remaining capacities, often reaching 80%. This secondary use in energy storage systems can relieve primary capacities [21]. The second life or resale of used vehicle batteries presents environmental and economic benefits by avoiding impacts associated with producing new batteries. However, reassembly for second use can also introduce emissions. In the case of FM Electric, battery resale could constitute secondary use, although long-term data are lacking to fully assess whether this practice will align with that of diesel tractor units. The current efforts in research and industry concerning recycling of vehicle materials, especially of lithium-ion batteries, indicate that a transition toward a cradle-to-cradle–like life cycle of BETs is emphasized and future innovations are expected to improve recycling capabilities.

5. Step 3: Life-Cycle Impact Assessment

Within the LCIA phase, the previously discussed material and energy needs are transferred to their equivalent CO_2e impact. This is performed individually by analyzing the phases of raw material extraction and component manufacturing, usage, and maintenance and recycling or end-of-life.

5.1. LCIA: Raw Material Extraction, Component Manufacturing, and Vehicle Assembly

In analyzing the greenhouse gas (GHG) emissions from raw material extraction and component manufacturing, the overall emissions per material were calculated using the GREET® database. The database offers a broad list of materials, often presented for different material variants or applications. Exemplary, for calculating the battery emissions the database category "MHDV: Combination Long-Haul Truck—Electric—Lithium-Ion battery—Bill of Material—Pathway" was chosen, as it presents the most fitting model for the desired use case. The underlying data has its origin in the "BatPaC"-model, which was created by the Argonne National Library, peer-reviewed several times since its creation in 2007, and last updated in 2023. The bill-of-material emissions were combined with the assembly emissions derived from the "Lithium Ion (Battery Assembling Process)" category of GREET®. In a similar fashion, the most suitable categories of the database were chosen for PCBs, copper, rubber, synthetic, aluminum, cast iron, steel, and others by either choosing a category connected to the vehicle type or material variants usually installed in heavy-duty trucks and checking the underlying data for sufficient actuality and quality. Furthermore, all material production processes were allocated through extensive literature research to their likely geographical location. For example, the production of the battery was set to China, while the final assembly of the vehicle was set to Sweden. The database allows the selection of a specific electricity mix with corresponding emissions. This way, every production step was connected to the likely electricity mix emissions in order to increase the precision of the production analysis.

Components made from steel, plastic, rubber, miscellaneous materials, and copper have similar CO_2e emissions ranging from approximately 1.9 to 3.7 kg CO_2e per kilogram of material. Cast iron exhibits the lowest GHG emissions at 0.508 kg CO_2e per kilogram, attributed to its full recyclability, eliminating environmental costs of resource extraction and transport. The highest emissions were noted for aluminum (11.581 kg CO_2e/kg) and the battery of the FM Electric (11.375 kg CO_2e/kg), driven by energy-intensive production and the use of rare resources, respectively.

Figure 6 illustrates the total GHG emissions for raw material extraction and component manufacturing for the FM Electric. The battery is identified as the primary source, accounting for 56% of GHG emissions (~34.13 t CO_2e), due to both high emissions per kilogram and its significant vehicle mass (3000 kg). Steel contributes 10% to the total emissions, despite being 32% of the vehicle mass, owing to relatively lower emissions per kilogram. Aluminum accounts for 11%, while PCBs contribute 14%. Rubber, plastic, cast iron, miscellaneous materials, and copper together account for less than 4%, due to lower mass or emissions per kilogram. The vehicle assembly phase also generates significant emissions. The GREET® model estimates emissions of 0.629 kg CO_2e per kilogram of assembled vehicle, totaling approximately 6242 kg CO_2e for the FM Electric. With 60.60 t CO_2e overall, the cradle-to-gate emissions are more than 3.5 times higher than those of the FM Diesel.

For the FM Diesel, GHG emissions were similarly analyzed. Aluminum and steel components emerged as the leading CO_2e sources. Aluminum is responsible for 34% of emissions (~5.84 t CO_2e) due to high emissions per kilogram (11.58 kg CO_2e /kg) and mass (504 kg). Steel, making up 44% of the FM Diesel's mass, contributes 32% to total emissions. Rubber and PCBs contribute 14% and 7%, respectively. Total raw material and component emissions for the FM Diesel are 17.13 kg CO_2e, as Figure 7 shows.

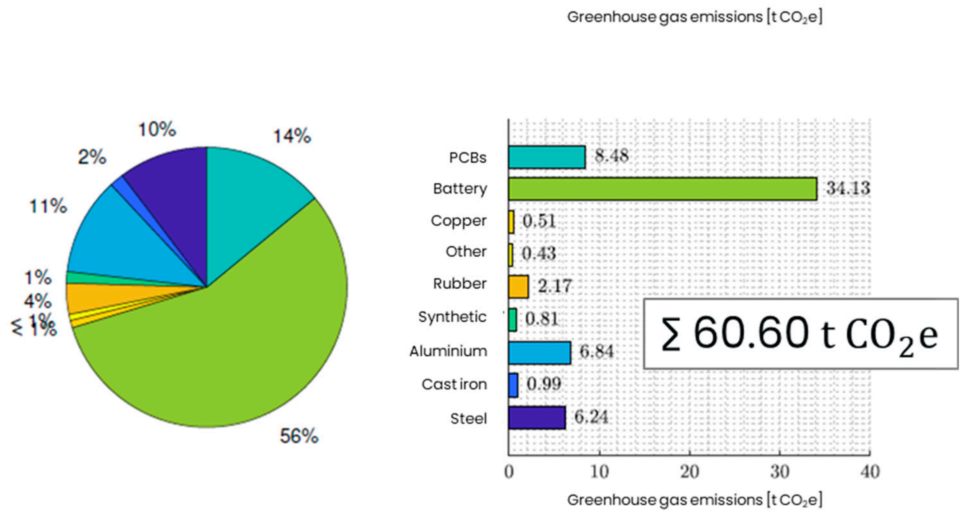

Figure 6. Emissions from resource extraction and component manufacturing of the Volvo FM Electric.

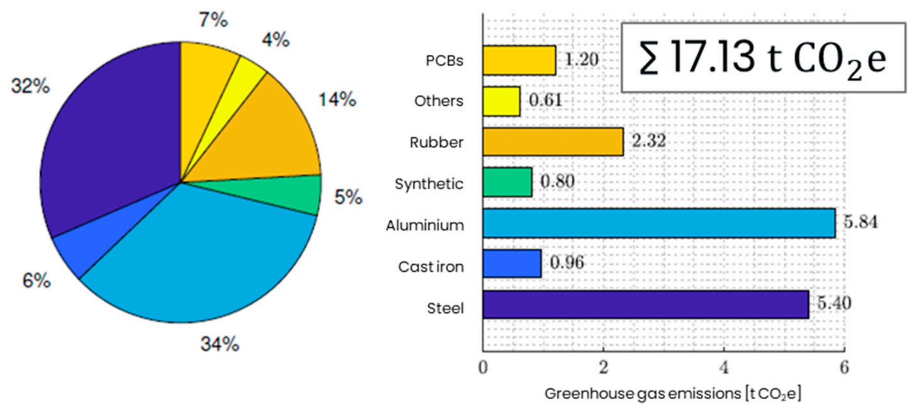

Figure 7. Emissions from resource extraction and component manufacturing of the Volvo FM Diesel.

Vehicle assembly for the FM Diesel results in approximately 3964 kg CO_2e, contributing 19% to life-cycle emissions. Overall, the cradle-to-gate emissions for the FM Diesel amount to 21,088 kg CO_2e, with 91% attributable to raw material and component production.

5.2. LCIA: Usage and Maintenance

The maintenance-related environmental costs of the FM Electric, including emissions from repairs and spare parts, are set at 3.5% of the vehicle's cradle-to-gate emissions, excluding battery replacement due to its proposed life-cycle–long usage [22,23]. This results in an annual maintenance-related emission of 1.08 t CO_2e per electric tractor unit. Operational emissions are tied to the following criteria summarized in Table 2.

Table 2. Criteria for usage emission calculation (FM Electric).

Criteria	Value	Source
Lifetime	1 million km or 7 years (from 2023)	[5,6]
Annual mileage	130,000 km	Real-world data
Average energy consumption per 100 km	113.91 kWh	Real-world data
Emission factor per kWh (direct and indirect)	Variable to time	[24,25]

Emissions for electricity are tightly connected to the energy grid, in this case the German electricity mix. The lifetime of 7 years is a combination of the annual mileage from real-world data, as well as the expected total mileage of 1 million kilometers [5,6]. When evaluating a projected lifetime to the future, it is important to integrate the changes of the electricity mix and its emission intensity. As this introduces uncertainty, two scenarios for the future German grid mix were assumed. On the one hand, historical data from 1990 to 2022 were predicted until 2045 using Exponential Triple Smoothing (ETS) with a 95% confidence interval (scenario 1), thus resulting in a conservative scenario [24,26]. ETS offers the advantage of assigning greater weight to the latest observations while keeping historical information, thus making the development of the recent past more influential. Notably, the drop in emissions seen in 2020 was due to an overall decrease in energy demand during the pandemic, resulting in a relatively higher share of renewables. On the other hand, the T45-Strom scenario carried out by the Fraunhofer ISI suggests a significant reduction trend, aligning with Germany's carbon neutrality goals by 2045 [25]. The T45 trend therefore represents an optimistic scenario (scenario 2). Scenario 2 anticipates significant emissions reductions, with emissions in 2029 dropping to 23.8% of scenario 1 levels. Maintenance emissions remain constant at 1078.9 kg CO_2e annually, becoming proportionally larger as energy consumption-based emissions decrease. Figure 8 comparatively illustrates the two scenarios with scenario 1 in red and scenario 2 in blue.

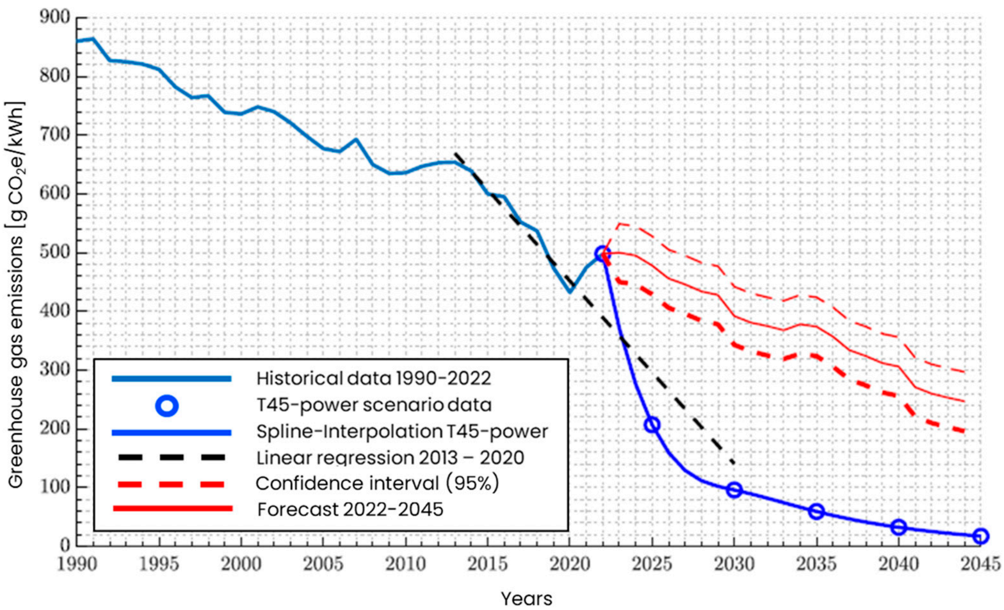

Figure 8. Electricity emission scenarios.

The analysis quantifies the annual greenhouse gas emissions attributable to the operation and maintenance of the FM Electric vehicle. This assessment utilizes a predefined annual mileage of 130,000 km, in conjunction with energy scenario–dependent emissions factors specific to the German electricity mix, and a consumption rate of 113.909 kWh/100 km. Notably, scenario 2, characterized by significantly lower specific emissions factors, results in a substantial reduction in the climate impact of the BETs from the outset. Specifically, emissions in scenario 1 are approximately 25.1% lower during the initial year. By 2029, emissions under scenario 2 decrease to approximately 23.8% of those observed in scenario 1. The emissions attributed to maintenance, which remain constant at 1078.9 kg CO_2e annually across both scenarios, reflect a proportional increase over time due to the relative decline in emissions associated with electricity consumption.

Life-cycle emissions stemming from vehicle operation and maintenance indicate a pronounced disparity, with total emissions in scenario 1, based on historical data, being approximately 2.4 times greater than those in scenario 2. Both scenarios exhibit maintenance contributions amounting to 7.552 t CO_2e, yet the relative contribution is considerably higher in scenario 2 due to differential electricity emissions. GHG emissions from usage and maintenance for the FM Electric are shown in Figure 9.

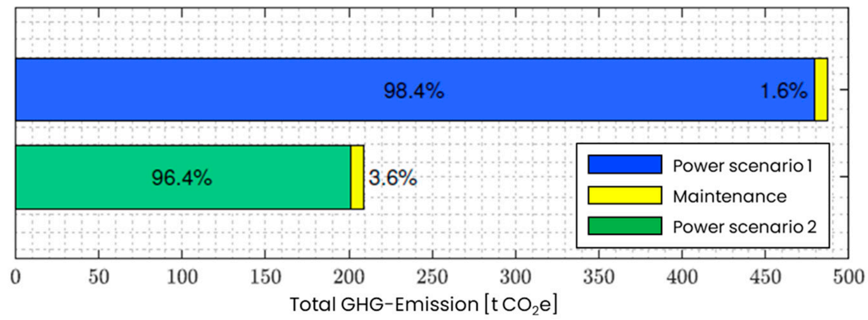

Figure 9. GHG emissions from usage and maintenance (FM Electric).

For the FM Diesel, maintenance costs are set at 3.75% of cradle-to-gate GHG emissions, translating into a comparatively low annual maintenance environmental cost of 0.7 t CO_2e. Key operational parameters are shown in Table 3.

Table 3. Criteria for usage emission calculation (FM Diesel).

Criteria	Value	Source
Lifetime	1 million km or 7 years (from 2023)	[5,6]
Annual mileage	130,000 km	Real-world data
Average energy consumption per 100 km	25.08 L	Real-world data
Average AdBlue® consumption per 100 km	2.081 L	Real-world data
Average motor oil consumption per year	34 L	Company interview
Emission factor per kWh (direct and indirect)	Variable to time	[27,28]

Diesel fuel consumption results in dominant emissions of 807.4 t CO_2e over the vehicle's lifespan, equivalent to 115.3 t CO_2e annually, due to the extensive use of 32,604 L of diesel per year, reflecting the significant climate impact per liter. Overall, fuel accounts for 97.9% of use-phase emissions, with maintenance representing 2.1%. GHG emissions from usage and maintenance for the FM Diesel are shown in Figure 10.

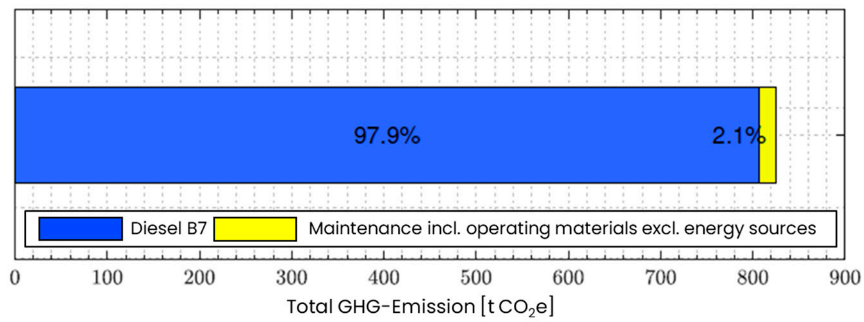

Figure 10. GHG emissions from usage and maintenance (FM Diesel).

5.3. LCIA: Recycling and End-of-Life

End-of-life scenarios can be categorized into disposal or recycling of materials. The mere disposal of lithium-ion batteries is highly problematic due to their toxic chemicals, heavy metals, and flammability [29]. Therefore, a recycling process is strictly necessary to preserve negative environmental effects beyond solely climate change.

In this end-of-life evaluation of vehicles, the theoretical recycling of the tractor units at the end of their service with Nord-Spedition is considered to mitigate the overall GHG footprint associated with vehicle production and disposal, thus reducing greenhouse gas emissions. Battery recycling is assumed to yield a conservative 15% reduction in production emissions [30,31]. For the rest of the vehicle, a 27% emission reduction is anticipated through recycling [32]. The emissions reduction as well as emission impact by the recycling processes are shown in Figure 11 with relatively higher emission savings for the FM Electric due to battery recycling. In addition, the emission savings through recycling have been calculated to be 4.3 t CO_2e for the FM Diesel, or 0.5% of the total life-cycle emissions. For the FM Electric, 11.7 t CO_2e could potentially be saved, resembling 2.1% of the life-cycle emissions. However, the potential of lithium-ion batteries is dependent on various factors such as second-life and ongoing innovation in recycling processes. Various scientific sources therefore estimate different impacts on the emission balance, thus leaving calculations as of now with uncertainty [33–35].

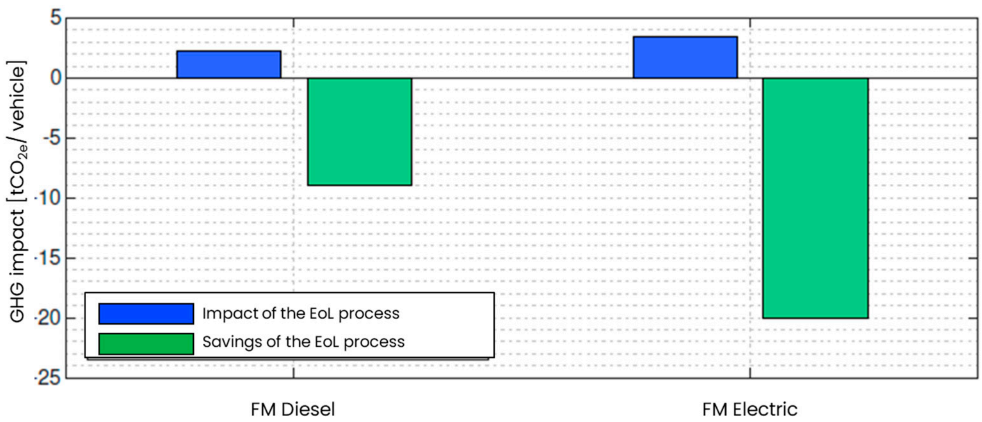

Figure 11. End-of-life emissions or emission savings.

6. Step 4: Interpretation (Discussion)

The following diagram shows the cumulating emissions from production, usage, and EoL for the two tractor unit types as well as for the two electricity scenarios from 2023 to 2029. Scenario 1 provides conservative estimates based on historical data, while scenario 2 anticipates future policy-driven improvements of the electricity mix. The overall CO_2e emissions for both vehicles are shown in Figure 12.

The FM Electric, despite having higher emissions during production, demonstrates superior environmental performance compared to a diesel tractor unit within just a few months due to significantly lower operational emissions. The breakeven point for greenhouse gas emissions is reached at approximately 97,500 km (in energy scenario 1) or 139,000 km (in energy scenario 2). Over its entire life cycle, the FM Electric can achieve savings from 34% (equivalent to 282 t CO_2e) up to 78% (equivalent to 565 t CO_2e) when compared to a diesel tractor unit, depending on the energy scenario. This highlights the importance of BETs as an environmentally friendly alternative as of 2023.

The environmental benefits of BETs can be further enhanced by reducing production emissions, especially through advanced recycling, combined with optimizing electricity generation from renewable sources. Both the FM Electric and diesel vehicles exhibit similar emissions for materials like plastics, cast iron, and rubber, but the FM Electric has 13.5% higher steel emissions and 14.8% higher aluminum emissions due to its reliance on these materials for its battery and structure. This additional aluminum helps reduce weight and improve battery range; however, significant emissions differences arise primarily from battery and printed circuit board production. The FM Electric's production emissions are considerably higher due to the battery alone contributing about half of the production emissions, with PCBs adding another 13.7%. This discrepancy identifies key areas for reducing BET emissions, especially through advancements in battery and PCB recycling. Effective recycling could notably decrease emissions, with battery recycling potentially reducing production emissions by 25%. In summary, the FM Electric shows significant potential for emissions savings over diesel tractor units, both currently and with expected progress in energy generation and materials recycling technologies. This analysis underscores the importance of integrating advanced recycling and further decarbonizing the power grid to fully realize these benefits.

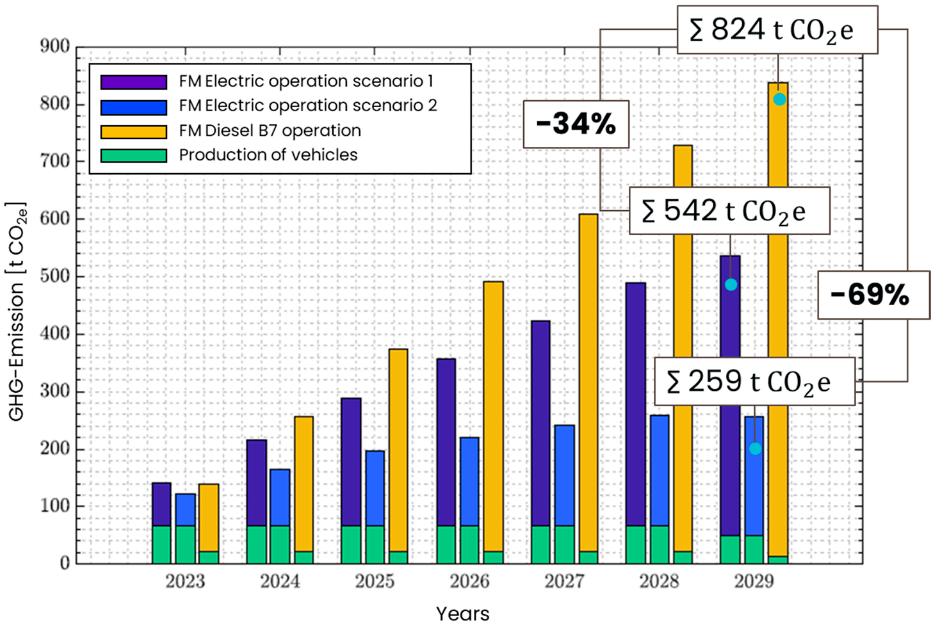

Figure 12. Cumulating overall CO_2e life-cycle emissions per truck type and electricity scenario.

Operational emissions, in contrast, significantly favor the BET. Over a 7-year lifespan, the FM Diesel emits markedly more than the FM Electric, with the latter's emissions decreasing alongside improvements in the energy mix. Increasing the use of renewable energy underscores the environmental benefits of BETs. Diesel's high-emission fuel dependency is a major drawback, and while biodiesel blending offers some promise, its feasibility is limited by land use and emission concerns, highlighting the demand for more sustainable solutions [36]. In this study, fuel consumption is comparable across studies, although differences in assumptions about vehicle manufacturing emissions exist. Other studies, such as those by ifeu and ICCT, estimate much higher manufacturing emissions compared to our findings. Our study reflects current electricity mixes and does not assume mid-life-cycle battery replacements, which significantly affect production emissions in other assessment models.

The comparison of CO_2e savings for BETs with two energy scenarios shows that despite the ambitious estimates in model studies, further investigation into the emissions from energy sources is necessary. The challenge of establishing a robust renewable energy network is critical, especially considering Germany's unique context of ongoing political crises that increase oil prices, its high freight transport volume as a transit land in Central Europe, and the nuclear phase-out, but achieving this could enhance the appeal and environmental benefits of electrifying heavy-duty vehicles [37–39].

The results of this study can be compared with the findings of the studies by ICCT and ifeu. When comparing the CO_2e reduction potential given an optimistic energy mix development, the ICCT study calculates a reduction potential of 76%, while the ifeu study results in 57%, compared to 69% of this research. Notable differences can be investigated within assumptions regarding recycling benefits and electricity grid development. The grid development of this study depends on the use case of the German electricity mix, which, compared to the European average of the other studies, is rather bad in terms of renewable energy use. This decreases the potential for emission reduction. Counteracting this, the production emission assuming recycling opportunities of this study are estimated to be low while the emission savings from battery recycling are estimated to be high, in reference to the two other studies. When comparing the conservative scenarios of the studies, meaning a low degree of recycling and slow transition of the energy grid, this study finds the smallest reduction potential with 34% in comparison to 63% (ICCT) and 48% (ifeu). This is due to the less sustainable energy mix within Germany relative to the European average, given that the transition toward renewable energies will not gain momentum in the coming years.

7. Conclusions

The potential emission reduction by BETs can be assessed using the data of the total German traffic sector emissions of 146 million t CO_2e in 2023, with 25% emitted by heavy-duty vehicles [1,2]. In the conservative scenario of 34% emissions reduction, 12.4 million t CO_2e could be saved annually. This reflects 9.5% of the total emissions of the traffic sector within Germany. In the optimistic scenario of a 78% reduction, up to 28.5 million t CO_2e or 19.5% of the traffic sector's emission impact could be reduced. These figures embrace the large leverage possible by utilizing BETs. However, the development must go hand in hand with the supporting expansion of the charging infrastructure, especially on highways, with high power charging and accessibility for tractor units. Additionally, the full potential of the technology requires a transition of the energy grid toward sustainable electricity generation from wind, water, sun, or other renewable sources.

This study utilized the GREET® model to aid vehicle life-cycle assessments with its extensive database. However, the inconsistency in data updates highlights a need for better industrial data integration for more accurate results. An update is particularly needed to consider the rapid changes in Germany's energy mix post-2022. Examining the electricity scenarios for BETs—both conservative and optimistic in terms of CO_2e abatement—revealed a significant disparity. This suggests that future analyses should refine their scope to enhance precision and reliability. The sustainability of the electricity mix is crucial; regions with high use of renewable energy observe greater climate benefits of BETs, while CO_2-intensive mixes reduce these advantages, highlighting the importance of global and national energy transitions.

End-of-life recycling is vital for reducing emissions and recovering valuable materials, particularly for batteries. The analysis shows that maintenance and consumables account for between 1.4% and 2.9% of life-cycle emissions. This underscores a need for more investigation into their environmental impact, although obtaining reliable real-world data remains a challenge. Assumptions for the recycling processes were minimized. Exploring real-world second-life and third-life uses of batteries, especially under differing regulations in other countries, could provide valuable insights.

BETs demonstrate superior energy efficiency due to their electric drivetrains. Nonetheless, issues such as limited range and the need for expanded charging infrastructure persist as significant challenges to higher utilization rates.

Moreover, conducting case studies on the operational use of heavy-duty tractor units in different contexts, such as cross-border long-distance transport, use cases outside Germany with different electricity mixes, alongside evaluation of various vehicle models like the Mercedes eActros, could provide deeper insights. As mentioned before, the environmental impact of BETs is not limited to CO_2e and climate change, thus further impact categories such as acidification, smog formation, or ecotoxicity should be analyzed to broaden the picture.

In conclusion, future research should focus on optimizing crucial factors like the electricity mix and recycling infrastructure to fully realize the ecological benefits of BETs and reinforcing them as a sustainable transport solution. This will significantly contribute to CO_2e emission reductions in transportation.

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Abbreviations

The following abbreviations are used in this manuscript:

BET	Battery–Electric Tractor Units
CO_2e	Carbon-Dioxide Equivalents
EoL	End-of-Life
ETS	Exponential Triple Smoothing
GHG	Greenhouse Gas
HDV	Heavy-duty Vehicle
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
VMA	Part-Manufacturing and Vehicle Assembly
WtP	Well-to-Product

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