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Article

# Life Cycle Assessment of Urban Electric Bus: An Application in Italy

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## Abstract

European energy and climate policies have enabled reductions in greenhouse gas emissions across many sectors, with transport standing out as an exception. In this area, one of the most promising solutions is the electrification of vehicles. In urban contexts, the shift towards electrifying transport—particularly local public transport (LPT)—can yield significant benefits, especially when paired with an increasingly decarbonized electricity mix, effectively reducing tailpipe emissions of both greenhouse gases and other pollutants. Nevertheless, it is essential to assess whether eliminating tailpipe emissions simply shifts environmental impacts to other stages of a vehicle's life cycle. The Life Cycle Assessment (LCA), employing a comprehensive cradle-to-grave approach, serves as the principal tool for such evaluations. In this framework, this study focuses on the Italian situation using a dynamic LCA for electricity mix. Results show that the electric bus reduces the impact on climate change (28.5 g CO<sub>2</sub>eq/pkm vs 66.7 g CO<sub>2</sub>eq/pkm for diesel, -57%), acidification, photochemical ozone formation, particulate matter, and the use of fossil resources. However, it presents higher impacts in terms of human toxicity (both carcinogenic and non-carcinogenic) and the use of mineral and metal resources, mainly due to batteries production and the use of metals such as gold, silver and copper.

**Keywords:** Life Cycle Assessment; electric bus; sustainable transport

## 1. Introduction

European energy and climate policies have led to reductions in greenhouse gas emissions in almost all sectors except for transport, where increased demand has more than offset the positive effects associated with increasingly stringent emission standards [1].

According to data published by the European Union in 2023 [2], greenhouse gas emissions from the transport sector, which had decreased in 2020 due to the pandemic, began to rise again in 2021, accounting for 26.7% of the Union's total emissions. Of these, 76.2% can be attributed to road transport. Heavy-duty vehicles, including buses, are responsible for approximately 28% of the total emissions from road traffic in the EU.

In this context, it is clear that achieving the decarbonization targets set by the European Green Deal [3] (-55% by 2030 and net zero emissions by 2050) cannot be accomplished without decisive interventions in the transport sector [4], the most significant of which is the electrification of transportation [5]. Whereas scientific research in the past primarily focused on passenger cars for private transportation, there has been a growing interest in decarbonizing heavy-duty transport, particularly local public transport (LPT) [6–10]. Although a comprehensive literature review is beyond the scope of the present paper, the studies reviewed suggest that a widespread increase in electric vehicles within local public transport fleets can lead to substantial benefits, especially when coupled with electricity mixes characterized by a high share of renewable energy sources [8]

In this regard, to encourage the electrification of public transport fleets, the European Directive EU 2019/1161 [11] (Clean Vehicle Directive)—implemented in Italy by the Legislative Decree 187/2021 [12]—sets minimum procurement targets for clean and energy-efficient vehicles for public administrations. The directive requires that, during the procurement process, the energy and

environmental impacts throughout the entire life cycle of these vehicles should be considered. In other words, it is essential to assess whether the absence of tailpipe emissions leads to a shift of impacts to other life cycle stages of so-called green vehicles. The Life Cycle Assessment (LCA) methodology—with its cradle-to-grave approach—proves to be the primary tool for such evaluations, as it enables the consideration of potential impacts linked to pollutant emissions and resource consumption throughout the entire life span of the analyzed vehicles: from the mining of materials required for the vehicle construction, through the production of energy carriers necessary for operation (electricity and diesel oil in this case), and including use phase (with maintenance), up to end-of-life management.

In this context, in the present study we carried out a Life Cycle Assessment of urban electric buses, comparing them with their diesel counterparts. The performance of the vehicles is evaluated using the Environmental Footprint (EF 3.0) method developed by the Joint Research Centre and recommended by the European Commission as a common European approach to measure the environmental performance of products [13]. As previously mentioned, several other studies have also addressed this topic. Limiting the view to the last years, Szczurowski [8] analyzes the electrification of the bus fleet in Krakow concluding that Electric buses can reduce total greenhouse gas emissions by 41.6% over their life cycle with a decarbonized electricity grid. García [14] compares hybrid and electric buses in Spain and in his analysis hybrid buses reduce LCA emissions by 40% (approx. 21 gCO<sub>2</sub>eq/km·passenger), and electric buses by 60% (approx. 12.5 gCO<sub>2</sub>eq/km·passenger) compared to diesel. Iannuzzi [15] studies hydrogen buses in Argentina founding that renewable hydrogen from biomass can avoid at least 70% of GHG emissions compared to fossil diesel, with values of 0.24-0.28 kgCO<sub>2</sub>eq/km versus 0.78 kgCO<sub>2</sub>eq/km for diesel. Jelti [16] conducts a Well-to-Wheel (WtW) LCA of alternative buses in Morocco. In his study Electric and fuel cell buses have zero direct emissions (TtW), but WtT impact depends on the energy mix. Gabriel [17] evaluates electric, CNG, and diesel buses in Bangkok and LCA emissions for electric buses are approximately 0.659 kgCO<sub>2</sub>eq/km, for CNG 1.117 kgCO<sub>2</sub>eq/km, and for diesel 2.0 kgCO<sub>2</sub>eq/km. Mastinu & Solari [18] compare electric and biomethane (CBG) buses. CBG performs better for global warming over the life cycle, while electric excels in human health and ecosystem quality. Al-Ogaili [19] highlights that electrification in Malaysia without grid decarbonization leads to increased CO<sub>2</sub> emissions. Zhao [20] analyzes charging infrastructure in Australia. In this case, due the high carbon intensity of the Australian electricity mix (approx. 0.944-1.05 kgCO<sub>2</sub>eq/km), electric Bus produces 1.2-1.4 times more GHGs than diesel (approx. 0.765-0.799 kgCO<sub>2</sub>eq/km), making grid decarbonization crucial.

In this context, the present study contributes to the literature with a comparative LCA of diesel and Electric urban buses focused on the Italian situation, with special attention to the electric mix that charges the electric bus batteries. On one side, the modelling relies on past detailed studies on the mix of technologies and energy sources used for electricity generation ([21–23]) on the other side we applied a “dynamic” LCA approach, taking into account the evolution of the Italian electric mix during the life span of buses (10 years) instead of considering future energy mix only for sensitivity analysis as for example in [8,24].

After this introduction, this paper follows the guidelines established by ISO 14040 [25]: methodology is hence described in chapter 2 (Goal and Scope ); main hypothesis and calculation methods are describe in chapter 3 (Life Cycle Inventory ), while chapter 4 (Results – Life Cycle Impact Assessment) discusses main results; finally the Interpretation of LCA results are discussed in chapter 5 (Conclusions).

## 2. Goal and Scope

The goal of this study is to assess the potential environmental impacts of electric and diesel urban public buses throughout their entire life cycle (cradle-to-grave approach) in the case of Italian cities. The overarching goal is to elucidate the key advantages and disadvantages of electrifying urban public transportation, thereby providing policymakers with robust evidence to inform the development of strategies for managing both public and private urban transport sustainably and to

support other researchers and LCA practitioners in evaluating LCA of urban buses. An attributional approach was adopted in the present analysis. [26].

### 2.1. Functional Unit

The functional unit defines the quantitative reference against which the environmental impacts of the analyzed systems are assessed. It serves as the basis for ensuring comparability across different technologies and operational scenarios.

This study compares two propulsion technologies for a 12-meter urban bus: one powered by diesel and the other by electricity. The functional unit selected for this analysis is the passenger-kilometer (pkm), which corresponds to the specific function of a bus transporting passengers along a given route.

The service life of the buses is assumed to be 800,000 km (80,000 km per year over 10 years) [27], and it is further assumed that the battery of the electric bus will be replaced once during the vehicle's operational lifespan [6]. The maximum passenger capacity is set at 102 passengers per vehicle [27]. By considering an average occupancy rate of 20% [28], the resulting value is 20.4 average passengers transported per vehicle. This value is consistent with data found in the literature: according to [6], the average occupancy is 16.04 persons per vehicle; The Ecoinvent database reports an average value of 21.1 persons per vehicle [29], while [30] indicates an average of 17.8 persons per vehicle in their research

### 2.2. System Boundaries

Authors adopted a cradle-to-grave approach, encompassing all stages of the bus life cycle: raw material extraction and processing, component manufacturing and vehicle assembly, energy carrier supply, use phase, maintenance, and end-of-life management.

### 2.3. Allocation

In this analysis, allocation procedures were generally not required for the main supply chains, except for the electricity when produced in combined heat-and-power power plants; in this case an energy based allocation has been applied (refer to [31] for further details).

Regarding the general approach, a cut-off strategy was adopted, with the sole exception of batteries. For batteries, end-of-life material recycling was considered, along with an environmental credit attributed to the secondary raw materials produced by the recycling process itself.

### 2.4. Environmental Impact Categories

The assessment of potential environmental impacts throughout the life cycle (Life Cycle Impact Assessment, LCIA) is conducted using the Environmental Footprint Impact Assessment Method (EF Method) [32] developed by the Joint Research Centre and recommended by the European Commission as a common European method for measuring the environmental performance of products [13]. The impact categories included in the analysis are presented in **Table 1**.

These categories are among the most frequently adopted in life cycle assessment (LCA) studies about the transportation sector [6].

**Table 1.** Impact categories of the Environmental Footprint method considered in this study, together with the respective indicators and characterization models.

Impact Categories	Functional Unit	Midpoint Indicator	Characterization Model
Climate change (CC)	kg CO <sub>2</sub> eq	Total global warming potential over the 100-year time horizon (GWP100).	IPCC 2013 [33]

Photochemical ozone formation (POF)	kg NMVOC <sub>eq</sub>	Potential for photochemical ozone formation.	LOTOS-EUROS come applicato in ReCiPe 2008 [34]
Acidification (A)	Mol H <sup>+</sup> <sub>eq</sub>	Accumulated exceedance of the critical load of acidifying substances in terrestrial and freshwater ecosystems.	Superamento accumulato AE (Accumulated Exceedance) [35,36]
Particulate matter (PM)	Disease incidence.	Impact on human health due to exposure to PM <sub>2.5</sub> particulate matter (disease incidence)	UNEP-SETAC Task Force (TF) on PM [37]
Human toxicity, non-cancer (HT-NC)	CTUh(*)	Increase in non-carcinogenic morbidity in the total population per unit of chemical compound emitted	USEtox, UNEP/SETAC Life Cycle Initiative [38]
Human toxicity, cancer (HT-C)	CTUh	Increase in carcinogenic morbidity in the total population per unit of chemical compound emitted	USEtox, UNEP/SETAC Life Cycle Initiative [38]
Resource use, fossils (RU-E)	MJ	Depletion of abiotic resources, fossil fuels (MJ)	Abiotic Resource Depletion, "ultimate reserves" [39]
Resource use, minerals and metals (RU-M)	kg Sb <sub>eq</sub>	Depletion of abiotic resources, minerals and metals (kg Sb eq.)	Abiotic Resource Depletion, "ultimate reserves" [39]

(\*) Comparative Toxic Unit for humans.

### 3. Life Cycle Inventory

In the following sections, the technical specifications representative of the buses and the description of the data used for modelling each life cycle phase are reported. Regarding background data, the main reference is the Ecoinvent 3.8 database [40].

Reference was then made to the GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model) to describe the production and maintenance phases of the vehicles [41].

The inventory of the lithium-ion battery was developed thanks to the activities carried out within the work described in [42] and updated in [43] which relies on primary data from an Italian battery producer.

In the following paragraphs, detailed information is provided for each life cycle phase considered.

#### 3.1. Vehicles and Batteries Production

As previously mentioned, the modelling of the bus production phase is based on the GREET model and, more specifically, on the section dedicated to Medium Heavy-Duty Vehicles (MHDV) [41].

The GREET model provides a quantitative description of three different heavy-duty vehicles configurations, specifying the components included in each and their respective material compositions. A comprehensive breakdown of these components is available in Appendix A (Tables A1–A3). Among the several available vehicles, Model 1—Class 6 PnD Trucks (Pick-up and Delivery)—was selected, as it most closely resembles the 12-meter urban bus considered in this study in terms of configuration (e.g. number of axles and tires), engine power (250 kW) and overall weight. To better reflect the specific characteristics of urban buses, The GREET data were adjusted to account for the higher content of materials such as glass and fabrics/polymers, which are typically more prevalent in buses than in trucks. To adapt the GREET data to the bus model, the EPD declaration of the Urbino 12 hybrid bus was used as a reference [27].

Table 2 shows the components and their respective weight for the two bus models considered, following the data reprocessing. Detailed data on original GREET subcomponents and adaptation to our case studies are reported in Supplementary information.

**Table 2.** Weight of the components of the electric bus (BEB) and the Diesel bus (ICEB) considered in this study (Source: GREET, RSE elaborations).

Systems	BEB (kg)	ICEB (kg)
Body	5046.53	5046.53
Chassis (w/o battery)	3717.56	3717.56
Electronic Controller	13.00	0.00
Fluids	87.60	123.75
Lead-Acid Battery	31.30	62.60
Li-Ion Battery	2995.00	0.00
Powertrain System (including BOP)	0.00	644.96
Traction Motor	134.00	0.00
Transmission System/Gearbox	90.00	221.00
Totale complessivo	12115.00	9816.40

Electricity consumption per vehicle assembly is 3,108 kW, while Heat consumption per vehicle is 5,574 MJ [41]. As for emissions during the painting phase of vehicles, the following emissions are assumed per vehicle: 1.6 kg of VOC, 0.02 kg of CO, 0.03 kg of NO<sub>x</sub>, 0.06 kg of PM<sub>10</sub>, and 0.03 kg of PM<sub>2.5</sub> [41].

In the absence of specific data, the end-of-life phase for buses was handled as in [44], initially considering that the end-of-life treatment process for cars could be extended to buses. Specifically, the end-of-life treatment involves a manual dismantling stage, which is followed by mechanical shredding and subsequent post-shredding operations with an overall recycling rate of about 80% [45].

We assumed that the electric bus is equipped with an NMC-type battery; the system includes 5 battery packs, with a total capacity of 395 kWh, and the battery weight is 2,995 kg, reflecting the specification of the Solaris NMC High Energy battery installed on the Urbino 12 electric bus [46].

The LCA modeling was carried out assuming a NMC 712 battery model (Lithium Nickel Manganese Cobalt oxide, LiNi<sub>0.7</sub>Mn<sub>0.1</sub>Co<sub>0.2</sub>) as it has an energy density close to that of the electric Solaris electric bus battery (approximately 140 Wh/kg for the reference battery versus 131 Wh/kg). As stated, the inventory of the lithium-ion battery was developed thanks to the activities carried out within the work described in [42] and updated in [43] which relies on primary data from an Italian battery producer. The modelling of energy consumption during the battery production phase was carried out under the assumption that the cells are manufactured in China and the battery pack is assembled in Europe.

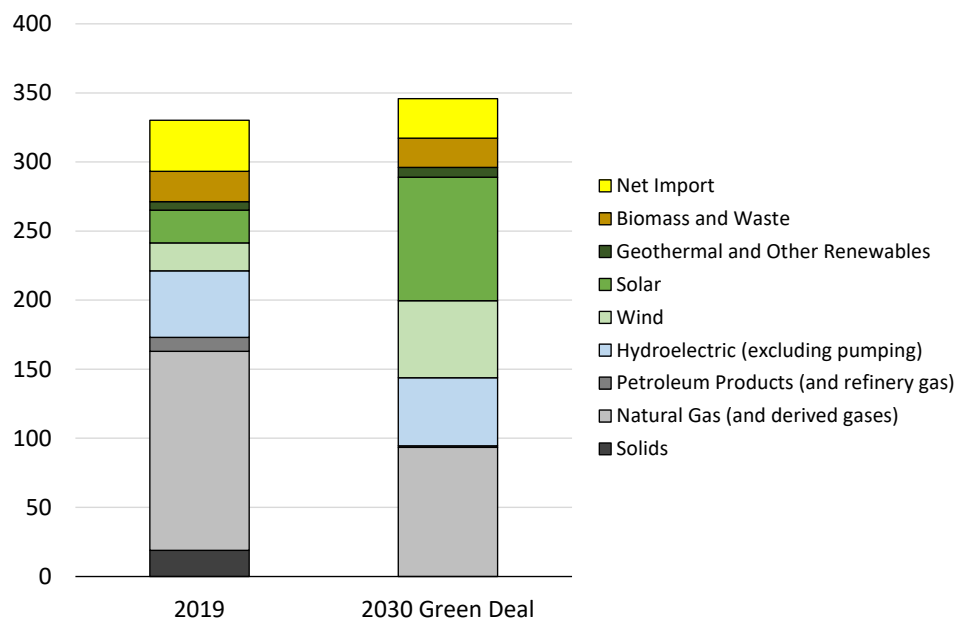
The end-of-life treatment for the batteries involves a two-step process comprising pyrometallurgical and hydrometallurgical procedures, performed sequentially. These processes enable the recovery of copper, cobalt sulfate, nickel sulfate, and manganese sulfate. The end-of-life modelling was based on the study by Cusenza et al. [47]

### 3.2. Electricity and Fossil Fuels

According to the so-called dynamic approach in LCA, the Italian electricity mix considered for charging the batteries of electric buses considers the gradual decarbonization of the country's power system over the vehicle's ten-year lifespan. This mix, is defined as a linear combination of the Italian electricity mix for 2019 and the 2030 mix (Green Deal policy scenario), referring to a vehicle produced

in 2019 and reaching its end of life in 2030. Assumptions and results for 2019 Italian Electric mix and the 2030 Italian electricity mix are taken from [22] and updated based on [48,49].

The composition by source of the electricity supply mixes used in the study is shown in Figure 1. In line with the progressive decarbonization of the electricity sector, the supply mixes for 2019 and 2030 correspond to carbon intensities of 395 gCO<sub>2</sub>eq/kWh and 153 gCO<sub>2</sub>eq/kWh, respectively.



**Figure 1.** Electricity supply mix by energy source for the years 2019 and 2030.

Concerning other life cycle phases, the following assumptions apply: Electricity consumption during maintenance, as well as that related to diesel refining and distribution, is represented by the average energy mix over the vehicle's lifetime (just as the charging mix for batteries); The energy mix for vehicle end-of-life processes is fixed at the 2030 scenario.

For vehicle and battery production phases, since these are assumed to occur outside of Italy, the reference is to the electricity mixes provided by Ecoinvent (European mix for vehicle production and battery assembly, Chinese mix for cell production).

The diesel oil burned in the internal combustion engine bus consists of a blend of mineral diesel and biodiesel with a 7% volume blend (as per UNI EN 590 standard [50]), in line with [51]. The production of biodiesel used in Italy in terms of share of domestic production and import as well as the type of biomasses employed and their geographical origin, reflects the data published by GSE for the year 2019 [52] and hence is quite different from what is suggested in Ecoinvent database for European market. Moreover, since biomass is certified as "sustainable", it means that no change in land use occurred for its production. For these reasons, neither land use change (from forest to crop) nor furans emissions (usually due to forest intentionally burned to leave spaces to cropland) have been considered.

### 3.3. Use Phase

Energy consumption values are taken from the literature and are assumed to be 1.25 kWh/km for the electric bus [53] and 38.04 l/100km for the Diesel bus [54].

Vehicle use-phase emissions include direct emissions from fuel combustion (for the internal combustion engine vehicle only) and those from brake, tire, and road surface wear.

For direct emissions, the average emission factors for road transport in Italy published by ISPRA for 2020 [54] were used. The reference buses are those classified as Urban Buses Standard 15 - 18 t,

compliant with the Euro VI D/E standard. Emission factors per km used in the study are reported Table 3.

**Table 3.** Emission factors per tons of diesel burned [54].

<b>Pollutant</b>	<b>Emission Factor [t/t] Urban</b>
CO	8.85E-04
NO <sub>x</sub>	1.64E-03
NM VOC	1.29E-04
CH <sub>4</sub>	1.65E-05
N <sub>2</sub> O	1.31E-04
NH <sub>3</sub>	2.83E-05
PM exhaust	2.80E-05
CO <sub>2</sub>	3.16E+00
SO <sub>2</sub>	1.43E-05
Pb Exhaust	4.89E-11
Cadmium exhaust	6.76E-09
Copper exhaust	1.15E-06
Chromium exhaust	3.68E-08
Nickel exhaust	4.72E-08
Selenium exhaust	6.79E-09
Zinc exhaust	6.81E-07
Benzene	9.04E-08
Indeno(1,2,3-cd)pyrene	4.65E-09
Benzo(k)fluoranthene	2.02E-08
Benzo(b)fluoranthene	1.81E-08
Benzo(a)pyrene	2.99E-09
Dioxins	5.31E-16
Furans	7.97E-16

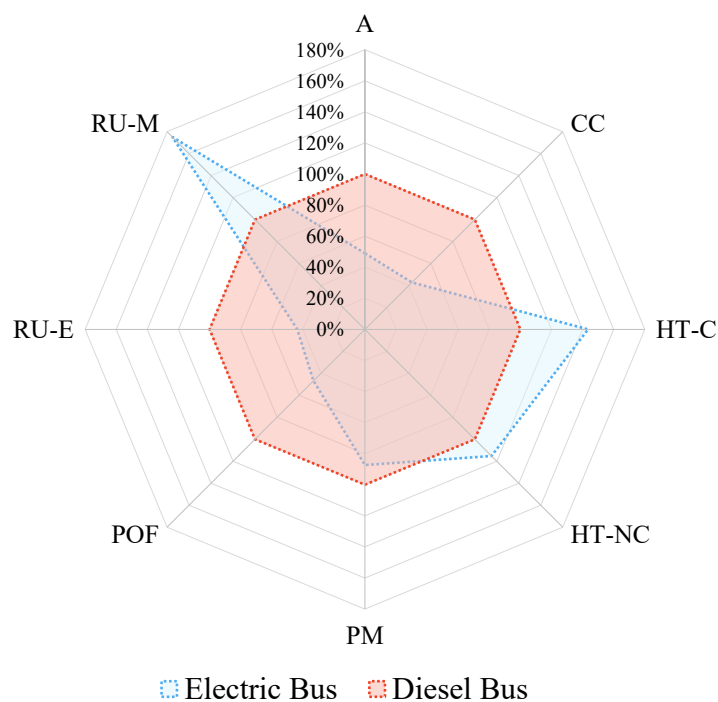
Wear-related emissions are assessed using specific datasets provided by Ecoinvent, based on data published by EMEP/EEA in the Air Pollutant Emission Inventory Guidebook [55,56]. These emissions are modeled as proportional to the total weight of the vehicle, including transported passengers.

The maintenance phase is modelled using data published by GREET [41], which have been adapted for this case study and account for the replacement of tires, fluids, oil filters, windshield wiper blades, and lead-acid batteries (for ICE buses) throughout the operational lifespan of the vehicles. Table A4 in Appendix A shows the number of replacements and the quantities replaced for the analyzed vehicles.

#### 4. Results – Life Cycle Impact Assessment

This chapter describes the results obtained from the comparison between electric and diesel buses from a life cycle perspective and in relation to the service provided, namely the transport of one passenger over one kilometer in an urban context. In particular, the performances of the vehicles according to the EF 3.0 method (indicators in Table 1), are illustrated.

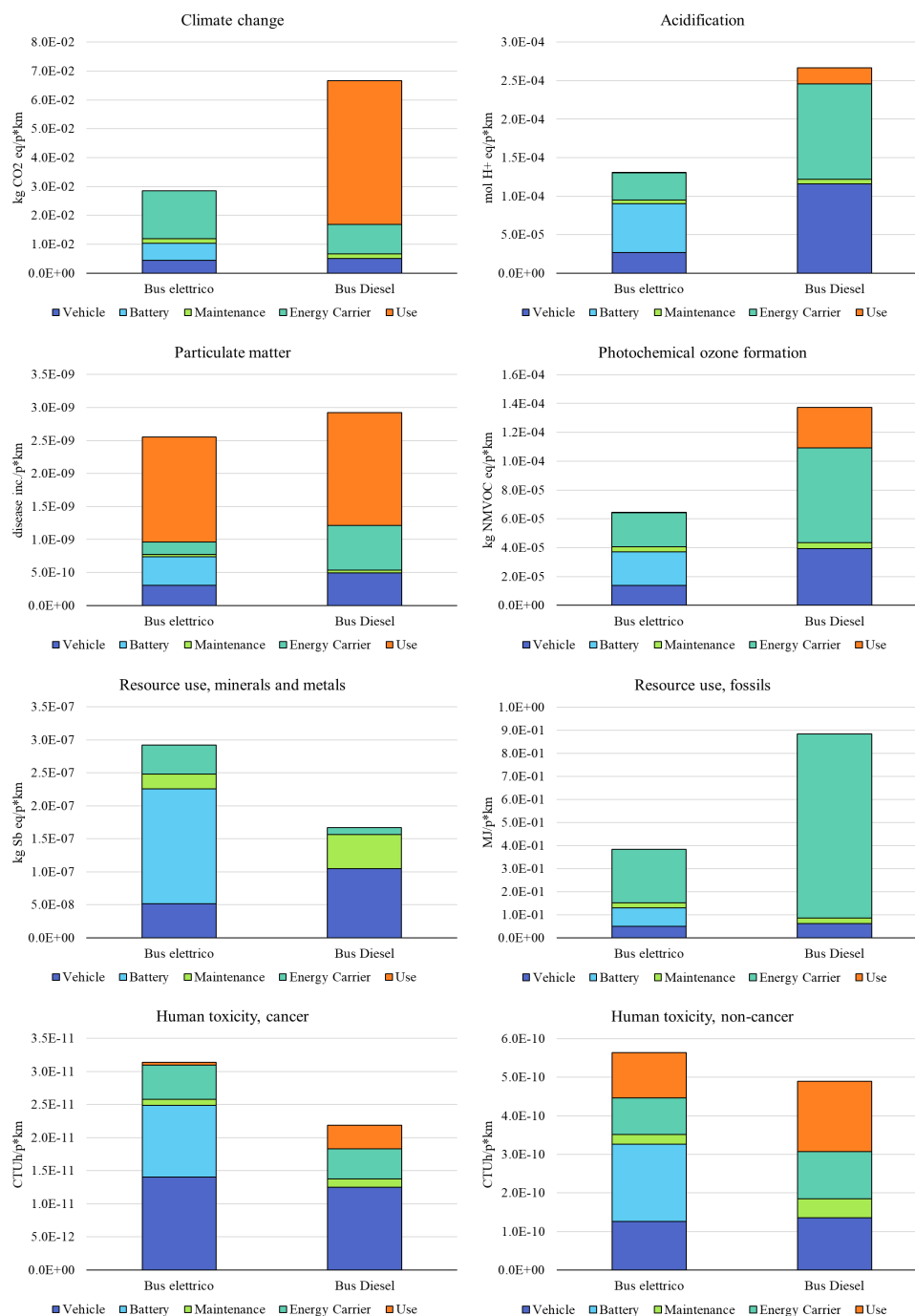
Figure 2 presents the environmental comparison between the two buses under study over their entire life cycle and for selected impact categories. In the graph, the reference value (100%) is assigned to the Diesel bus. The results highlight the potential contribution of electric buses to both the decarbonization of public transport and the improvement of the quality of life in urban areas. The electric bus shows lower potential impacts related to climate change (CC), acidification (A), particulate matter formation (PM), photochemical ozone formation (POF), and energy resource use (RU-E). However, it should be noted that the electric bus performs worse than the diesel bus in terms of human toxicity, both cancer and non-cancer related (HT-C and HT-NC), and, even more markedly, in Resource Use Mineral and metals (RU-M).



**Figure 2.** Potential impacts related to the two bus powertrains in an urban driving cycle. In the graph, the reference point (100%) is represented by the performance of the Diesel-powered bus. CC = Climate Change; HT-C = Human toxicity, cancer; HT-NC = Human toxicity, non-cancer; PM = Particulate matter; POF = Photochemical ozone formation; RU-E = Resource use, fossils; RU-M = Resource use, minerals and metals; A = Acidification.

Figure 3 shows the contribution of each life cycle phase to the selected impact categories. For the Climate Change impact category, the potential impacts for electric and diesel buses are 28.5 and 66.7 g CO<sub>2</sub>eq/p\*km, respectively, with a percentage difference of 57%. For the diesel bus, the predominant contribution is attributable to the use phase (75% of the total). Regarding Acidification and Photochemical Ozone Formation, the electric bus demonstrates the best performance, and it is observed that, for the diesel bus, potential impacts from the diesel oil supply phase are particularly significant. The Particulate Matter impact category shows that the performance of the two vehicles is rather similar. In fact, the lower impacts associated with the electric powertrain are offset by those related to the battery life cycle. Moreover, the use-phase contribution is comparable for both vehicles and is essentially due to wear from brakes, tires, and road surfaces (for the diesel bus, wear accounts for 90% of potential particulate emissions in the use phase, and 100% for the electric bus). The consumption of fossil energy resources follows a trend analogous to that of climate change, while the use of mineral resources highlights the real weakness of the electric bus. Specifically, for the electric vehicle, a substantial share of the value of this indicator (Resources Use – Minerals and Metals) is due to battery production and end-of-life, which alone accounts for 60% of the indicator's overall value. The main drivers of this impact are the consumption of gold, silver, and copper (and tellurium,

connected to copper production) used in battery manufacturing (including BMS). The percentage difference between the indicator values for the two vehicles is approximately 75%. Moreover, the potential impacts related to human toxicity (both cancer and non-cancer) penalize the electric bus, once again due to the potential impacts associated with the battery's life cycle.



**Figure 3.** Potential environmental impacts of the analyzed vehicles across selected impact categories (EF 3.0 method). Values are expressed per passenger-kilometer; Vehicle: includes production and end-of-life of the vehicle; Battery: includes production and end-of-life of the NMC battery; Maintenance: includes vehicle maintenance and disposal of replaced components; Energy carrier: includes electricity and Diesel supply; Use: includes exhaust and non-exhaust emissions.

As illustrated by the figures, multiple impact categories are significantly influenced by both the production of the energy carrier (whether electricity or diesel fuel) and the use phase. This, in turn, suggests that these impacts are primarily influenced by the bus's energy consumption. According to

a brief literature review, there is considerable variability in energy consumption values, ranging from 110 kWh/100 km [6] to 170 kWh/100 km [45] for electric buses, and from 26 l/100 km [46] to 63.17 l/100 km [30] for diesel buses (see supplementary Information). However, the uncertainty analysis performed using the Monte Carlo method showed that the ranking of vehicle performance remains unchanged across the range of consumption values. For further details on this analysis, please refer to Appendix B.

Comparing different LCA studies is always difficult due to the differences in hypotheses, system boundaries, background databases and of course to selected environmental impact categories and related calculation methods. However, one of the most used impact categories is Climate Change and, hence, we compared our results with other LCA studies on electric buses. To this end we made a harmonization of results in terms of total mileage and average occupancy rate. More in detail, results from other studies were harmonized using the following reference parameters: a useful vehicle lifetime of 800,000 km and an average occupancy of 20.4 passengers per vehicle. In cases where original data were not available, harmonization was performed on a vehicle-kilometer basis and then converting to passenger-kilometers using the 20.4 passenger figure and assuming a similar bus lifespan. If sources provided a different passenger occupancy, the value was converted to reflect 20.4 passengers. Where total mileage was not declared a default value of 800,000 km was assumed.

As shown in Table 4, our results are in line with other literature studies, although a certain degree of variability is observed. This variability is mainly due to differences in the energy mix used and to the assumptions for the maintenance phase, in particular, to the number of battery substitutions during the vehicle lifetime.

**Table 4.** Harmonized Climate Change bus for Electric Bus.

Study	Year	Scenario	Original Value	Original Unit	Original Useful Life	Original Occupancy Factor	Harmonized Value (g CO <sub>2</sub> eq/pkm)
This study (RSE)	Dynamic 2019-2030	E-bus (Dynamic IT mix)	28.5	g/pkm	800,000	20.4	28.5
Nordelöf et al. [6]	2019	Electric (EU mix)	48	g/pkm	780,000	16	37.7
O'Connell et al [57]	2021-2040	BEV (EU grid)	22.9	g/pkm	881000	20.4	22.9
Syré et al [58].	2024	BEV bus (EU)	n.d.	g/km	70000	39 (60*65%)	24.25 (for Urbino 12 in EU scenario)
Luu et al. [30]	2022	E-bus (Vietnam)	108.11	g/pkm	320000	17.8	37.8
García et al. [24]	2022	Electric Bus (total LCA, current)	12.5	g/km.passenger	800,000	80	49.02
Jelti et al. [16]	2021	Electric Bus (total WTW)	5,174	T CO <sub>2</sub> eq/year (fleet)	n.d.	n.d.	47.02
Gabriel et al. [17]	2021	Electric Bus (total LCA)	6.14 × 10 <sup>5</sup>	kg CO <sub>2</sub> -eq (per bus)	930,750	46	32.34
Zhao et al. [20]	2021	Electric Bus (total LCA, incl. infrastructure)	690,549.6	kgCO <sub>2</sub> e (per station/bus)	650,000	n.d.	52.06

## 5. Conclusions

This comparative Life Cycle Assessment (LCA) of electric and diesel buses, conducted using the Environmental Footprint (E.F.) 3.0 method, provides a detailed evaluation of the environmental impacts associated with each type of bus. The results show that in the Italian scenario, electric buses offer significant advantages over diesel buses across most impact categories. Specifically, electric buses demonstrate reduced environmental impacts in areas such as climate change, acidification, and eutrophication. These findings are consistent with other LCA studies, underlying the advantages of BEBs particularly when the carbon footprint of the electricity mix is below 705 gCO<sub>2</sub>eq/kWh. Moreover, when the electricity mix falls below 200 gCO<sub>2</sub>eq/kWh, BEBs can outperform even buses powered by HVO in terms of environmental performance.

However, the study also highlights certain areas where electric buses do not perform as well. Notably, the impact categories of "resource use, minerals and metals," "human toxicity, cancer," and "human toxicity, non-cancer" show higher impacts for electric buses compared to their diesel counterparts. These findings underscore the importance of considering the entire life cycle of electric buses, including the extraction and processing of raw materials used in battery production and a wide range of impact categories.

Overall, the transition to electric buses presents a promising pathway towards reducing the environmental footprint of public transportation. Nevertheless, it is crucial to address the identified challenges related to resource use and human toxicity to fully realize the environmental benefits of electric buses. Future technological development should focus on improving battery technology and recycling processes to mitigate these impacts and enhance the sustainability of electric buses, while policy should promote circular economy to reduce impact on resource use and on use of critical raw materials.

Although our study relies on detailed data on consumption and emission factors for what concerns diesel buses as well as on detailed data on energy mix and cell production for electric buses, future research would benefit from primary data from bus manufacturers, on battery pack composition and, for electric buses, on road real data on maintenance and consumption.

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**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors on request.

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## Appendix A. Life Cycle Inventory Additional Information

### *Busses Composition*

Below are detailed supplementary notes which integrate the modelling framework described in Chapter 3.

Table A1 provides a list of components included in the GREET model and their respective descriptions. These components served as the foundational basis for the modelling of bus BOMs.

**Table A1.** Systems and subsystems present in GREET used to model Urban Busses in the present work.

System	Subsystems	Description of Individual Parts
Body system	Cab-in-white	Primary MHDV structure, i.e., a single-body assembly to which the other major components are attached
	Body Panels and Fairings	Closure and hang-on panels, including hood, roof, decklid, doors, quarter panels, and fenders, as well as fairings
	Front/Rear Bumpers	Impact bars, energy absorbers, and mounting hardware
	Glass	Front windshield, and windows (door, side, and sleeper)
	Lighting	Exterior: Head lamps, fog lamps, turn signals, side markers, front top markers, and rear light assemblies Interior: Wiring and controls for interior lighting, instrumentation, and power accessories
	Heating, Ventilation, Air Conditioning (HVAC) Module	Air flow system, heating system, and air conditioning system (includes a condenser, fan, heater, ducting, and controls)
	Seating and Restraint System	Seat tracks, seat frames, foam, trim, restraints, anchors, head restraints, arm rests, seat belts, tensioners, clips, air bags, and sensor assemblies
	Door Module	Door insulation, trim assemblies, speaker grills, and switch panels and handles (door panels are part of body panels)
	Instrument Panel	Panel structure, knee bolsters and brackets, instrument cluster (including switches), exterior surface, console storage, glove box panels, glove box assembly and exterior, and top cover
	Trim and Insulation	Emergency brake cover, switch panels, ash trays, cup holders, headliner assemblies, overhead console assemblies, assist handles, overhead storage, pillar trim, sun visors, carpet/rubber, padding, insulation, and accessory mats
	Body Hardware	Miscellaneous body components

	Engine Unit	Engine block, cylinder heads, shafts, fuel injection, engine air system, ignition system, manifolds, alternator, containers and pumps for the lubrication system, gaskets, and seals
Powertrain system	Engine Fuel Storage System	Fuel tank, tank mounting straps, tank shield, insulation, filling piping, and supply piping
	Powertrain Thermal System	Water pump, radiator, and fan
	Exhaust System	Catalytic converter, muffler, heat shields, and exhaust piping
	Powertrain Electrical System	Control wiring, sensors, switches, and processors
	Emission Control Electronics	Sensors, processors, and engine emission feedback equipment
Transmission Unit		Clutch, gear box, final drive, and controls Use of automated manual transmission system
	Cradle	Frame assembly, front rails and cross-members, and cab and body brackets (the cradle bolts to cab-in-white and supports the mounting of engine)
	Driveshaft/Axle/ Inter-axle Shaft	Propeller shaft that connects gearbox to the differential Half shaft that connects wheels to the differential; Shafts that connect front and rear parts of a tandem drive axle
Chassis system	Axles	Steer (single) and drive (tandem) axles A gear set that transmits energy from driveshaft to axles and allows for each of the driving wheels to rotate at different speeds while supplying them with an equal amount of torque
	Differential	Upper and lower shock brackets, shock absorbers, springs, steering knuckle, and stabilizer shaft
	Suspensions	Hub, disc, rotor, splash shield, and calipers
	Braking System	Steer and drive axle wheels and tires
	Wheels and Tires	Steering wheel, column, joints, linkages, bushes, housings, and hydraulic- assist equipment
	Auxiliary	

Electric drive system	Generator	Power converter that takes mechanical energy from the engine and produces electrical energy to recharge batteries and power the electric motor for series
Electric drive system	Traction Motor	Electric motor used to drive the wheels
Electric drive system	Electronic Controller	Power controller/phase inverter system that converts power between the batteries and motor/generators for electric drive vehicles
Battery system	ICEV	Pb-acid battery to handle startup and accessory load
Battery system	EV	Pb-acid battery to handle mainly startup load, Li-ion battery for use in electric drive system
Fluid system	ICEV	Engine oil, engine/powertrain coolant with coolant cleaner, brake fluid, windshield fluid, transmission fluid, power steering fluid, lubricant oils, and adhesives
Fluid system	EV	Powertrain coolant with coolant cleaner, power steering fluid, brake fluid, transmission fluid, windshield fluid, lubricant oils, adhesives
Van/Box system	Body	Front, sides, floor, and roof of van/box, along with auxiliary parts
Lift-gates system	Lift-gates	Gates used for loading/unloading of goods, along with their hydraulic systems and other constituent parts

The composition by material of the constituent components of the electric and diesel buses is presented in Tables A2 and A3, respectively. This composition is the result of an elaboration of data published by GREET for the MHDV model, designated as Class 6 PhD, and is based on the findings of the Environmental Product Declaration (EPD) for the Solaris Urbino 12 hybrid bus manufactured by Solaris [27].

**Table A2.** Material composition of the components of the electric bus.

System	Material	Mass (kg)
Body		5.05E+03
	<i>Cast aluminum</i>	2.39E+02
	<i>Copper</i>	2.37E+01
	<i>Cotton paper</i>	6.21E+00
	<i>Glass</i>	3.63E+02

	<i>Glass fiber-reinforced plastic</i>	7.65E+02
	<i>Graphite</i>	7.50E+00
	<i>Latex</i>	2.21E+02
	<i>Leather</i>	1.15E+02
	<i>Plastic</i>	6.76E+02
	<i>Rubber</i>	1.36E+02
	<i>Silica</i>	7.50E+00
	<i>Stainless steel</i>	1.84E+02
	<i>Steel</i>	1.88E+03
	<i>Wrought aluminum</i>	4.27E+02
Chassis (w/o battery)		3.72E+03
	<i>Brass</i>	2.78E-01
	<i>Cast aluminum</i>	1.89E+02
	<i>Cast iron</i>	3.43E+02
	<i>Copper</i>	8.83E-01
	<i>Magnet</i>	5.37E-01
	<i>Plastic</i>	2.17E+00
	<i>Rubber</i>	2.50E+02
	<i>Steel</i>	2.93E+03
Electronic Controller		1.30E+01
	<i>Alumina</i>	3.89E-02
	<i>Average Plastic</i>	1.31E-01
	<i>Cast aluminum</i>	6.95E+00
	<i>Copper/Brass</i>	3.95E+00
	<i>Epoxy resin</i>	2.55E-02
	<i>Fiberglass</i>	8.04E-02
	<i>Nickel</i>	2.14E-02
	<i>Nylon</i>	9.38E-03
	<i>PET</i>	3.59E-01
	<i>Polypropylene</i>	5.12E-01
	<i>Polyurethane</i>	2.55E-01
	<i>Rubber</i>	1.61E-01
	<i>Steel</i>	3.66E-01
	<i>Zinc</i>	1.33E-01
	<i>Zinc oxide</i>	2.68E-03
Lead-Acid Battery		3.13E+01
	<i>Fiberglass</i>	6.63E-01
	<i>Lead</i>	2.18E+01
	<i>Plastic (polypropylene)</i>	1.92E+00
	<i>Sulfuric Acid</i>	2.49E+00
	<i>Water</i>	4.45E+00
Li-Ion Battery		3.00E+03

Traction Motor	1.34E+02
<i>Cast aluminum</i>	4.23E+01
<i>Copper/Brass</i>	1.16E+01
<i>Enamel</i>	5.23E-01
<i>Epoxy resin</i>	1.03E+00
<i>Glass fiber</i>	1.34E-02
<i>Methacrylate ester resin</i>	1.74E-01
<i>Mica</i>	4.02E-02
<i>Nd(Dy)FeB magnet</i>	3.85E+00
<i>Nickel</i>	4.02E-02
<i>Nylon</i>	1.34E-02
<i>Paint/Varnish</i>	4.29E-01
<i>PBT</i>	2.14E-01
<i>PET</i>	4.29E-01
<i>Phenolic resin</i>	6.70E-02
<i>Silicone</i>	5.36E-02
<i>Stainless steel</i>	8.98E-01
<i>Steel</i>	7.23E+01
<i>Zinc</i>	1.34E-02
Transmission System/Gearbox	9.00E+01
<i>Brass</i>	1.95E-01
<i>Cast aluminum</i>	5.28E+00
<i>Cast iron</i>	2.18E+01
<i>Magnet</i>	1.90E-02
<i>Plastic</i>	9.55E-02
<i>Rubber</i>	9.55E-02
<i>Steel</i>	6.21E+01
<i>Wrought aluminum</i>	3.60E-01
Fluids	8.76E+01
<i>Steer axle</i>	7.00E+00
<i>Drive axle</i>	5.87E+00
<i>Inter-axle/Drive shafts</i>	1.40E+01
<i>Wheel-end: Steer axle</i>	8.62E+00
<i>Wheel-end: Drive axle</i>	8.62E+00
<i>Transmission Fluid</i>	2.35E+00
<i>Powertrain Coolant</i>	1.68E+01
<i>Coolant cleaner</i>	1.71E+01
<i>Windshield Fluid</i>	7.19E+00
Total	1.21E+04

**Table A3.** Material composition of the components of the Diesel bus.

<b>System</b>	<b>Material</b>	<b>Mass(kg)</b>
Body		5.05E+03
	<i>Cast aluminum</i>	2.39E+02
	<i>Copper</i>	2.37E+01
	<i>Cotton paper</i>	6.21E+00
	<i>Glass</i>	3.63E+02
	<i>Glass fiber-reinforced plastic</i>	7.65E+02
	<i>Graphite</i>	7.50E+00
	<i>Latex</i>	2.21E+02
	<i>Leather</i>	1.15E+02
	<i>Magnet</i>	0.00E+00
	<i>Plastic</i>	6.76E+02
	<i>Rubber</i>	1.36E+02
	<i>Silica</i>	7.50E+00
	<i>Stainless steel</i>	1.84E+02
	<i>Steel</i>	1.88E+03
<i>Wrought aluminum</i>	4.27E+02	
Chassis (w/o battery)		3.72E+03
	<i>Brass</i>	2.78E-01
	<i>Cast aluminum</i>	1.89E+02
	<i>Cast iron</i>	3.43E+02
	<i>Copper</i>	8.83E-01
	<i>Magnet</i>	5.37E-01
	<i>Plastic</i>	2.17E+00
	<i>Rubber</i>	2.50E+02
Lead-Acid Battery	<i>Steel</i>	2.93E+03
		6.26E+01
	<i>Fiberglass</i>	1.33E+00
	<i>Lead</i>	4.35E+01
	<i>Plastic (polypropylene)</i>	3.85E+00
	<i>Sulfuric Acid</i>	4.98E+00
Powertrain System (including BOP)	<i>Water</i>	8.90E+00
		6.45E+02
	<i>Bronze</i>	5.05E-02
	<i>Cast aluminum</i>	2.69E+01
	<i>Cast iron</i>	2.37E+02
	<i>Ceramic</i>	4.75E+01
	<i>Copper &amp; Brass</i>	1.96E-01
	<i>Graphite</i>	1.88E-02
	<i>Nichrome</i>	1.68E+00
	<i>Plastic</i>	4.29E+01

	<i>Platinum</i>	3.16E-01
	<i>Rubber</i>	2.06E+00
	<i>Stainless steel</i>	2.67E+01
	<i>Steel</i>	1.85E+02
	<i>Wrought aluminum</i>	7.42E+01
Transmission System/Gearbox		2.21E+02
	<i>Brass</i>	4.78E-01
	<i>Cast aluminum</i>	1.30E+01
	<i>Cast iron</i>	5.36E+01
	<i>Magnet</i>	4.67E-02
	<i>Plastic</i>	2.35E-01
	<i>Rubber</i>	2.35E-01
	<i>Steel</i>	1.53E+02
	<i>Wrought aluminum</i>	8.84E-01
Fluids		1.24E+02
	<i>Engine Oil</i>	1.53E+01
	<i>Steer axle</i>	7.00E+00
	<i>Drive axle</i>	5.87E+00
	<i>Inter-axle/Drive shafts</i>	1.40E+01
	<i>Wheel-end: Steer axle</i>	8.62E+00
	<i>Wheel-end: Drive axle</i>	8.62E+00
	<i>Transmission Fluid</i>	7.65E+00
	<i>Powertrain Coolant</i>	2.45E+01
	<i>Coolant cleaner</i>	2.50E+01
	<i>Windshield Fluid</i>	7.19E+00
Total		9.82E+03

Table A4 presents the components replaced during maintenance and the number of replacements carried out over the service life of the vehicle. The values were calculated, based on those published by GREET, considering the assumed service life for the buses.

**Table A4.** Components replaced during maintenance and the number of replacements performed.

<b>Type of component</b>	<b>Spare parts</b>	<b>N. substitution</b>
<b>Fluids</b>		
	<i>Engine Oil (ICEB only)</i>	13
	<i>Steer axle</i>	6
	<i>Drive axle</i>	0
	<i>Inter-axle/Drive shafts</i>	16
	<i>Wheel-end: Steer axle</i>	0
	<i>Wheel-end: Drive axle</i>	0
	<i>Transmission Fluid</i>	5
	<i>Powertrain Coolant</i>	2
	<i>Coolant cleaner</i>	2
	<i>Windshield Fluid</i>	73

<b>Battery</b>	<i>Lead Acid</i>	6
	<i>Li-Ion</i>	1
<b>Tyre</b>	<i>Steer Tyre</i>	3
	<i>Drive Tyre</i>	2
<b>Other components</b>	<i>Windshield Wiper Blades</i>	25
	<i>Engine oil filter (ICEB only)</i>	10

## Appendix B. Monte Carlo Analysis

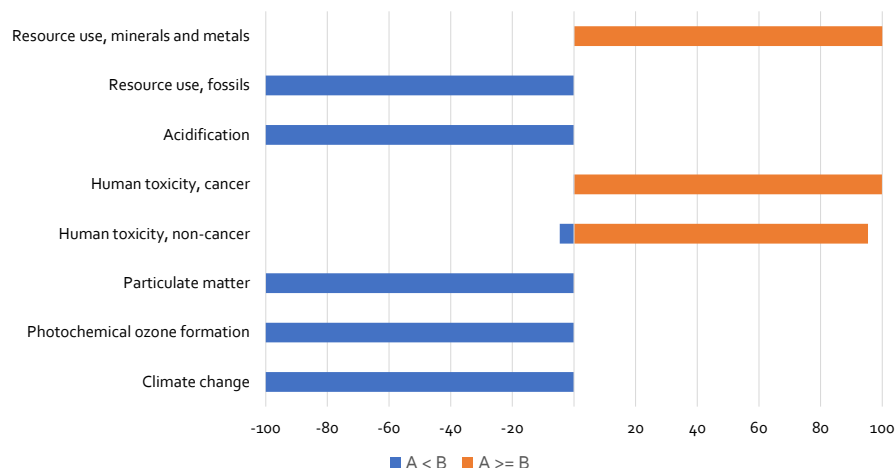
Table A5 Shows energy consumption for diesel and electric buses reported in several literature studies.

**Table A5.** Energy consumption for diesel and electric buses literature.

	<b>Diesel</b> <b>(l/100km)</b>	<b>Elettrico</b> <b>(kWh/100km)</b>
Nordelöf et al, 2019 [6]	45	110
Basma et al., 2020 [59]	55.7	170
ISPRA 2020 [54]	38.04	n.a.
Ecoinvent [40]	63.17	n.a.
et al., 2022 [8]	42	150
Luu et al., 2022 [30]	26	136
Mastinu e Solari, 2022 [18]	n.a.	125
Green Bocconi, 2021 [60]	n.a.	115
Söderena et al., 2019 [61]	28	n.a.
Motus-E, 2022 [5]	n.a.	127
Zhou et al., 2016 [62]		138
Zhou et al 2016 [62]		175
Zhao et al., 2021 [7]	29.20	120
Doulgeris et al., 2024 [63]	n.a.	96
Doulgeris et al., 2024 [63]	n.a.	220
<b>Min value</b>	<b>26</b>	<b>96</b>
<b>Max value</b>	<b>63.17</b>	<b>220</b>
<b>Best guess value</b>	<b>38.04</b>	<b>115</b>

The robustness of the ranking obtained for the performance of the buses was assessed through an uncertainty analysis based on the Monte Carlo method. For this purpose, it was assumed that consumption values follow a triangular probability distribution, with minimum and maximum values corresponding to the lowest and highest values (for the two vehicles) found in the literature. The simulation was carried out with 10,000 iterations and a confidence level of 95%.

Figure A1 presents the results of the Monte Carlo analysis for the transportation of one passenger over one kilometer using an electric bus (A) and a diesel bus (B), taking into account the impact categories of the EF 3.0 method.



**Figure A1.** Monte Carlo analysis for the transport of 1 passenger-kilometer with electric and diesel buses. The values shown represent the probability of the difference between the potential impacts of the electric bus (A) and those of the diesel bus (B).

The analysis reveals that, for all indicators except human non-carcinogenic toxicity, the ranking established by the baseline assessment is confirmed. For instance, regarding the Climate Change indicator (as reported in the graph), the probability that the value calculated for the electric bus is lower than that for the diesel bus ( $A < B$ ) is 100%. A similar result is observed for the impact categories Acidification, Resource Use–Fossil, Particulate Matter, and Photochemical Ozone Formation. Conversely, there is a small probability (4.6%) that the human non-carcinogenic toxicity associated with the electric bus is lower than that due to the diesel bus. Lastly, the probability that the impact categories Resource Use–Minerals and Metals and Human Toxicity–Cancer are in favor of the electric bus is zero.

## Abbreviations

The following abbreviations are used in this manuscript:

A	Acidification
AE	Accumulated Exceedance
BMS	Battery Management System
BOM	Bill Of Materials
CC	Climate Change
CLCC	Commodity Life Cycle Costing
CTUh	Comparative Toxic Unit for human
EEA	European Environment Agency
EF	Environmental Footprint
EMEP	European Monitoring and Evaluation Programme
EPD	Environmental product Declaration
REET	The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GWP100	Global Warming Potential 100 years
HT-C	Human toxicity, cancer
HT-NC	Human toxicity, non-cancer
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MHDV	Medium Heavy-Duty Vehicles
NMC 712	Lithium Nickel Manganese Cobalt oxide $\text{LiNi}_0.7\text{Mn}_0.1\text{Co}_0.2$
PM	Particulate matter
POF	Photochemical ozone formation
RU-F	Resource use, fossils
RU-M	Resource use, minerals and metals

RdS	Ricerca di Sistema
RSE	Ricerca Sistema Energetico
TPL	Trasporto Pubblico Locale

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