Article citation info:
Przytuła I, Burchart D. Greenhouse gas assessment of urban buses based on environmental product declarations – a review. Combustion Engines. 2026;205(2):32-38. https://doi.org/10.19206/CE-211727

Iga PRZYTUŁA
Dorota BURCHART

Combustion Engines
Polish Scientific Society of Combustion Engines

Greenhouse gas assessment of urban buses based on environmental product declarations – a review

ARTICLE INFO

Received: 14 June 2025
Revised: 30 September 2025
Accepted: 6 October 2025
Available online: 31 October 2025

The paper presents a review study about comparative life cycle assessment (LCA) of selected 12-meter urban buses powered by hybrid, battery-electric, and hydrogen fuel cell systems. The review is based on Environmental Product Declarations (EPDs) and follows ISO 14040/44 standards, using a cradle-to-grave approach and a functional unit of 1 passenger-kilometer. Environmental impacts are assessed across raw material extraction, production, operation, maintenance, and end-of-life stages. Results of the review show that the operation phase has the highest share of total greenhouse gas emissions, particularly when fossil-based energy is used. For electric and hydrogen buses, upstream processes also contribute significantly due to material and component complexity. The findings highlight the role of energy mix and vehicle structure in determining the total impact, stressing the importance of full life cycle assessment in evaluating sustainable transport solutions. EPD can be the first step for developing a Digital Product Passport (DPP) for the buses.

Key words: *life cycle assessment, public transport, environmental product declaration, alternative fuels*

1. Introduction

In recent years, environmental considerations have gained increasing importance in the public transport sector, particularly in bus transport. Faced with growing pressure to reduce greenhouse gas emissions and improve energy efficiency, local authorities and transport operators are seeking low-emission and zero-emission solutions. This shift is particularly relevant in light of the fact that road transport causes about 25% of EU greenhouse gas emissions, the second-largest source after energy. [14]. In response, a key direction in the decarbonization of urban mobility is the implementation of alternative fuels such as electricity, hydrogen, biofuels, and synthetic fuels, whose environmental impacts can vary significantly depending on the technology used and the energy source.

To reliably assess the environmental performance of buses used in public transport, it is essential to apply the Life Cycle Assessment (LCA) methodology, which enables a comprehensive evaluation of environmental impacts across all stages of a vehicle's life. This approach covers the production phase – including the extraction and processing of construction materials – as well as the operational phase, maintenance activities, and the final dismantling and disposal of the vehicle at the end of its service life. Considering all phases gives a clearer view of a transport solution's environmental burden.

LCA makes it possible to assess not only emissions generated during daily operation but also hidden environmental burdens such as natural resource consumption, emissions from component manufacturing, and the impact of maintenance processes. In the case of buses powered by alternative fuels, this method allows for the consideration of specific drivetrain technologies, energy storage systems, and technical maintenance requirements, which can significantly influence the overall environmental profile. As a result, it becomes feasible to identify the life cycle stages that contribute most significantly to the total environmental impact and to develop strategies for effectively reducing the overall environmental footprint of bus fleets, including through material selection, energy efficiency improvements, or the implementation of circular economy principles.

The LCA method currently represents the most comprehensive tool for environmental analysis, enabling the assessment of not only greenhouse gas emissions but also a wide range of other impact categories such as resource depletion, acidification, eutrophication, and toxicity [15, 16]. Despite its complexity, the method identifies key life cycle stages and guides stakeholders in reducing impacts.

Recent years have seen a growing number of LCA studies on diesel, hybrid, battery-electric (BEB) and fuel cell buses (FCEB). These analyses confirm that the environmental performance of public transport technologies depends mainly on the electricity mix, hydrogen production pathways, vehicle lifetime, and battery size. For example, studies on Polish and Spanish bus fleets show that while BEBs significantly reduce GHG emissions, their benefits strongly depend on energy intensity per kilometer and power sector decarbonization [9, 22]. Hybrid buses can provide meaningful interim GHG reductions (~40% lower life-cycle CO_2) with negligible cost increases [9]. At the same time, research from Bangkok demonstrates that BEB and CNG buses reduce human health and ecosystem damage by up to 55% and also incur lower life-cycle costs [8]. In turn, hydrogen-based LCA studies stress that only "green" hydrogen enables substantial GHG reductions (> 70%). In contrast, conventional hydrogen offers limited advantages [11]. Comparative modelling further indicates that both BEB and FCEB can deliver significant climate benefits if powered by low-carbon energy [13].

In this context, the importance of Environmental Product Declarations (EPD) becomes evident. They support the ESG agenda by ensuring: Environmental transparency of carbon and resource indicators; Social benefits through reduced air pollution; and Governance compliance with EU taxonomy and sustainable procurement. Embedding LCA insights into ESG frameworks allows municipalities and operators to demonstrate that bus technology choices contribute not only to decarbonization but also to broader sustainability governance in public transport.

The objective of this review study is to evaluate and compare the environmental performance of 12-meter urban buses powered by hybrid, battery-electric, and hydrogen fuel cell systems, using the Life Cycle Assessment (LCA) methodology applied in verified Environmental Product Declarations (EPDs). By adopting a boundary system and a functional unit, the analysis aims to identify the key life cycle stages contributing to total environmental impacts, with particular focus on greenhouse gas emissions, as well as to highlight the role of energy mix, vehicle design, and material composition in shaping overall results. The study also seeks to demonstrate the usefulness of EPD-based LCA as a transparent and standardized tool for supporting climate policy objectives, guiding sustainable fleet planning, and serving as a basis for future Digital Product Passports (DPPs) in the bus sector.

2. The role and relevance of environmental declarations in public transport

Type III Environmental Product Declarations (EPDs) are a key instrument for assessing the environmental performance of public transport vehicles [14]. They deliver standardized, independently verified data from Life Cycle Assessment (LCA) in line with ISO 14040/44, enabling fair comparison across technologies. The main recipients are policymakers, transport operators, manufacturers, and procurement authorities, who use EPDs to integrate environmental criteria into fleet planning, procurement, and climate strategies. Covering all stages of the life cycle – from raw material extraction to production, use, and end-of-life treatment, EPDs provide a transparent basis for sustainable decision-making. In practice, they support evidence-based policy, guide investments in low-emission fleets, and strengthen market competitiveness through verified environmental performance. They are also increasingly applied in public tenders, benchmarking of vehicle technologies, monitoring compliance with environmental standards, and as a foundation for future Digital Product Passports (DPPs). Furthermore, EPD-based assessments contribute to research and innovation by identifying environmental hotspots, thereby supporting the development of more resource-efficient and circular design solutions.

Environmental Product Declarations are voluntary manufacturer documents that require third-party verification to comply with ISO 14025 [14]. Thanks to their standardized format and credibility, they are widely applied in B2B contexts to assess the environmental impact of components and raw materials in final products. In the public transport sector – particularly in bus transportation – Environmental Product Declarations (EPDs) are still relatively uncommon. To date, only a limited number of vehicle manufacturers have chosen to develop such declarations as evidence of the reduced environmental impact of their products throughout the entire life cycle. Limited uptake results from the voluntary nature of EPDs and the effort needed for full LCA with third-party review. Nevertheless, the growing emphasis on sustainability, coupled with increasing regulatory and public pressure for transparency in environmental performance, may encourage broader adoption of EPDs in the near future.

For public buses, an EPD includes an LCA covering all life cycle stages. As illustrated in Figure 1, the assessment begins with the extraction and transportation of raw materials, followed by the manufacturing of components and vehicle assembly. The completed vehicle is then delivered to the customer during the transportation stage, which, while less impactful, is included for completeness. The operation and maintenance stage typically represents the largest share of total emissions, particularly in conventionally fuelled buses, accounting for fuel or energy consumption and servicing over the vehicle's lifetime. Finally, the disposal stage covers end-of-life processes such as dismantling, material recycling, and waste treatment.

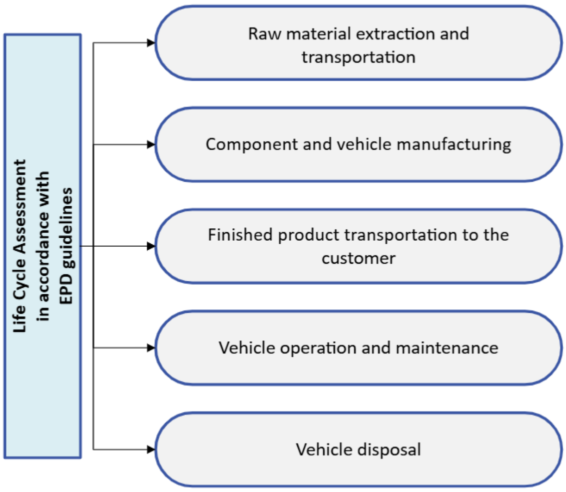

Fig. 1. Stages included in the LCA of transport vehicles in accordance with EPD guidelines

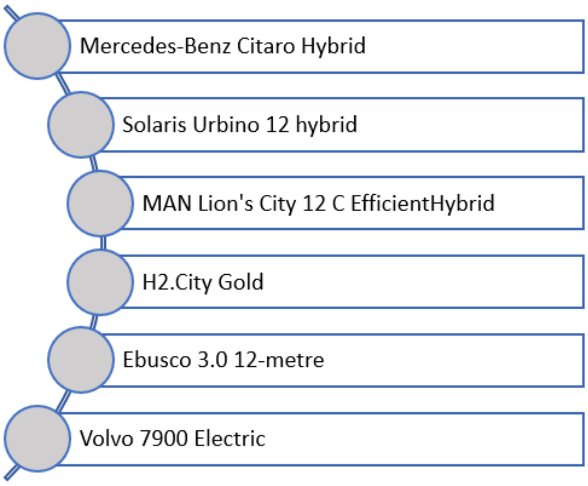

Fig. 2. Selected public transport vehicles for which EPDs have been developed

Based on data provided by the global environmental declaration program, Fig. 2 illustrates examples of Type III EPDs developed for public road transport vehicles [5]. All listed models are 12-meter city buses designed for urban operation. The group includes vehicles equipped with a range of low-emission technologies: hybrid systems (Mercedes-Benz Citaro Hybrid, Solaris Urbino 12 Hybrid, MAN Lion's City EfficientHybrid), battery-electric drivetrains (Volvo 7900 Electric, Ebusco 3.0), as well as hydrogen fuel cell propulsion (H2.City Gold).

The development EPDs is carried out in accordance with the guidelines defined in the Product Category Rules (PCR), which provide a standardized framework for conducting LCA and presenting the resulting environmental data for a specific group of products. PCR documents ensure consistency, comparability, and transparency across EPDs by specifying in detail the methodological approach, system boundaries, data quality requirements, and reporting formats appropriate for the given product category [12].

In the case of public transport vehicles – such as single-decker and double-decker buses, as well as articulated and standard models that fall under vehicle categories M1, M2, and M3 – the applicable PCRs are developed with reference to specific regulatory foundations. In particular, they are aligned with the provisions of Regulation (EU) 2018/858 of the European Parliament and of the Council. This regulation establishes uniform technical and administrative requirements for the approval and market access of motor vehicles designed for the transport of passengers and their luggage, thereby forming the legal and technical basis for defining the life cycle boundaries, product reference flows, and functional characteristics relevant to the assessment [7]. As a result, the environmental performance evaluation of such vehicles within EPDs is not only harmonized with EU regulatory frameworks but also tailored to the operational context and functional roles of vehicles in public transport systems.

Figure 3 presents the scope of LCA-based environmental assessments for public transport vehicles. The PCR documents define, among other things, system boundaries and required impact categories, enabling comparability of declarations across different manufacturers and technologies.

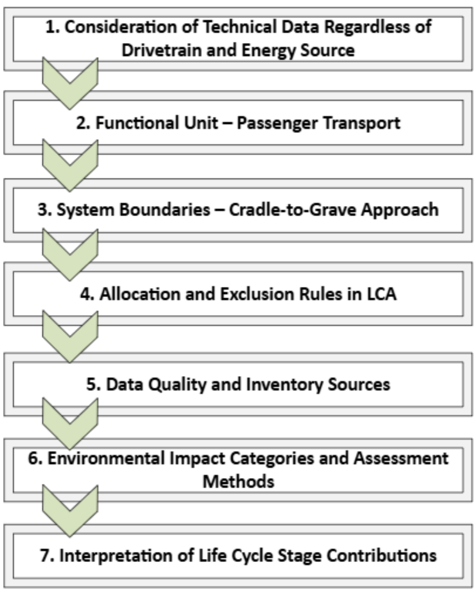

Fig. 3. PCR content for the environmental assessment of the life cycle of public transport

The process begins with the integration of full technical data regardless of the drivetrain type or energy source. This allows for the consistent assessment of all vehicle technologies – whether diesel, hybrid, electric, gas-powered, or hydrogen fuel cell – based on standardized parameters such as vehicle mass, dimensions, engine power, and passenger capacity.

The environmental performance is evaluated per a defined functional unit, typically one passenger-kilometer (1 pkm), which ensures comparability between different transport modes and operational profiles. The system boundaries are based on the cradle-to-grave model and are divided into three main life cycle phases:

a) Upstream: extraction and processing of raw materials, manufacturing of components and subsystems, and logistics associated with the delivery of materials to the production site
b) Core: vehicle production and final assembly within the manufacturer's facilities, including the integration of powertrain, bodywork, and systems. This stage also includes the transport of the finished product to the customer
c) Downstream: operational use of the vehicle, covering fuel or energy consumption, maintenance and repair processes, and end-of-life scenarios such as dismantling, material recovery, recycling, and waste disposal.

Each EPD must follow clear allocation and exclusion rules as set by the applicable Product Category Rules (PCR), ensuring that only relevant environmental impacts are considered and minor contributions (typically < 1%) can be justifiably excluded. The quality and reliability of data sources are critical, with a preference for empirical data from the manufacturer or reputable life cycle inventory (LCI) databases such as Ecoinvent or GaBi.

The assessment includes multiple impact categories – such as greenhouse gas emissions (GHG), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential (ADP), photochemical ozone creation potential (POCP), and water scarcity potential (WSP) – in accordance with standardized impact assessment methods. Finally, interpretation of the results should identify the relative contribution of each life cycle phase, enabling stakeholders to pinpoint environmental hotspots and implement targeted strategies for reducing the overall footprint of public transport systems.

3. Life cycle-based environmental assessment of 12-meter urban buses using EPD declarations

This chapter presents a comparison of six selected models of 12-meter urban buses, based on data obtained from their respective Environmental Product Declarations (EPDs). The analysis deliberately relies on EPDs, as they are prepared according to ISO 14025 and EN 15804 standards and provide third-party verified life-cycle data. The purpose of this approach is not to establish a new methodological framework, but to demonstrate how standardized and transparent information can be used to compare environmental performance across bus technologies. This perspective highlights the practical value of EPDs in supporting sustainable public procurement and ESG reporting, while ensuring data consistency and credibility. It should be noted that currently, only selected manufacturers choose to develop and publish EPDs for their vehicles, despite the fact that such documents offer one of the most transparent and reliable sources of environmental information. For example, in the case of hydrogen-powered buses based on fuel cells, only one EPD was available, which limits the possibility of fully evaluating this technology. The highest number of declarations was found for battery-electric and hybrid vehicles, reflecting growing interest in these technologies in the context of sustainable public transport and the need to meet climate policy targets. A detailed comparison of the selected vehicles, including passenger capacity, lifetime mileage, material composition, and recycling indicators, is provided in Table 1.

All analyzed declarations are based on a full life cycle approach (cradle-to-grave), covering raw material extraction, component and vehicle manufacturing, distribution, use, maintenance, and end-of-life treatment.

Data were extracted directly from the interpretation sections of the declarations, compiled into comparative tables, and examined to identify both the total carbon footprint and the relative contribution of individual life cycle stages. Differences in methodological assumptions between EPDs (e.g., databases, electricity mixes, system boundaries) were documented and discussed as part of the interpretation.

To ensure comparability across different propulsion technologies, only verified EPDs developed in line with ISO 14040/44 and ISO 14025 standards were included. These documents were selected as the primary data source because they provide standardized, independently verified LCA results prepared by manufacturers and reviewed by third parties.

Most vehicles have a reference life of 800,000 km, as set by Directive 2009/33/EC [6]. This value is considered representative for the typical operation of a city bus over 10–12 years. Deviations from this standard, such as in the case of the MAN Lion's City 12 C EfficientHybrid (1 300 000 km) or the Mercedes-Benz Citaro Hybrid (600,000 km), reflect manufacturer-specific assumptions based on durability expectations and intended operational conditions.

Passenger capacities range from 88 to 110 persons, with the highest values recorded for battery-electric vehicles – likely due to the use of lighter structural materials. A higher number of passengers contributes to a lower environmental impact per pkm, which is a notable advantage in terms of life cycle performance.

An analysis of material composition reveals clear differences between technologies. Hybrid vehicles are characterized by the highest share of metals – up to 74% of total mass – which supports high material recoverability. In contrast, zero-emission vehicles (BEVs and FCEVs) contain a significantly higher proportion of complex components, particularly electrical systems, batteries, and electronic equipment. In the case of the Ebusco 3.0, these components account for up to 30% of the vehicle's total mass. While beneficial from an operational perspective (no tailpipe emissions), this profile presents challenges at the end-of-life stage, particularly in relation to battery and composite material recycling.

The highest recyclability rates were recorded for hybrid buses: MAN – 96.4%, Solaris – 95.9%, Mercedes – 94.0%, which corresponds to their relatively simple and predictable material structures. Electric buses achieved slightly lower values: Volvo – 90.0%, Ebusco – 84.5%, mainly due to the use of composite and chemically complex battery materials. The hydrogen bus (H2.City Gold) scored 89.2%. However, full evaluation is hindered by the lack of data on overall recoverability, likely due to the absence of standardized end-of-life procedures for hydrogen storage tanks and fuel cell systems. The overall recoverability rate (including both material and energy recovery) reached the highest levels in hybrid buses – up to 99.0% – indicating strong potential for circular material flows. The lowest recovery rate was obser-

Table 1. Overview of selected 12-meter urban bus models based on Environmental Product Declarations (EPDs), including technical parameters and material recovery indicators

Nº	Brand of bus	Propulsion type	Functional unit	System boundary	Passenger capacity	Travelled distance	Material composition	Recyclability rate	Recoverability rate
1	Mercedes-Benz Citaro Hybrid [3]	HEV	1 pkm	Cradle-to-Grave	101	600 000 km	72.9% metals; 9.3% polymers; 4.8% glass; 13% others	94.0%	99.0%
2	Solaris Urbino 12 hybrid [21]	HEV			102	800 000 km	66.0% metals; 12.0% electric and electronic equipment; 9.0% polymers; 13.0% others	95.9%	96.1%
3	MAN Lion's City 12 C Effi-cientHybrid [17]	HEV			97	1 300 000 km	74.1% metals; 10.7% poly-mers;19,6% glass; 13.7% others	96.4%	98.2%
4	H2.City Gold [2]	FCEV			91	800 000 km	55.7% metals; 19.6% electric and electronic equipment; 11.0% polymers; 13.7% others	89.2%	–
5	Ebusco 3.0 [4]	BEV			110	800 000 km	46.0% metals; 30.0% battery and electric; 10.0% polymers; 14.0% others	84.5%	89.5%
6	Volvo 7900 Electric [23]	BEV			88	800 000 km	76.9% metals; 8.9% polymers; 4.8% glass; 9.4% others	90.0%	98.0%

Table 2. Total greenhouse gas emissions (GHG) and dominant life cycle phase contributions for six 12-meter urban buses according to EPD data

Nº	Type of bus	Total GHG emission [kg CO_2 eq.]	Analysis Results	GHG emission Determinants
1	Mercedes-Benz Citaro Hybrid [3]	0.0111	The operation phase dominates GHG emissions with 91.0%, indicating that fuel combustion during use is the primary contributor. Raw material supply contributes 6.9%, with notable influence on abiotic depletion of metals (88.3%) and water deprivation (39.1%). Maintenance has a minor GHG impact (1.4%) but contributes significantly to water deprivation (38.0%).	Operation 91.0%; Raw material acquisition 6.9%
2	Solaris Urbino 12 hybrid [21]	0.011	The highest environmental impact occurs during bus operation – responsible for 89.5% of greenhouse gas emissions, 53.2% of photochemical smog, 61.8% of water pollution (eutrophication), and nearly 90.0% of fossil fuel use. In contrast, raw material extraction and manufacturing have the greatest share in mineral depletion (91.1%) and water use (74.2%). Transport and end-of-life phases have minimal impact – below 1%.	Operation 89.5%; Raw material acquisition 5.9%
3	MAN Lion's City 12 C EfficientHybrid [17]	0.0138	Reducing lifetime mileage from 1.3 million to 800,000 km lowers total GHG emissions per vehicle by 36.9% (from 1736 to 1092 kg CO_2-eq). However, emissions per passenger-km increase slightly (from 13.77 to 14.07 g CO_2-eq/pkm). The use phase still dominates with 94% of total impact in the 800,000 km case.	Operation approx. 90.0%
4	H2.City Gold [2]	0.0116	Total GHG emissions per passenger-km are 0.0116 kg CO_2-eq. The downstream phase dominates (82.17%), with operation alone responsible for 78.3%. Upstream contributes 16.7%, core processes 1.1%, maintenance 3.2%, and end-of-life 0.7%.	Operation 78.3% ; Raw material acquisition 16.7%
5	Ebusco 3.0 [4]	0.00454	Total life cycle emissions: 399.916 kg CO_2-eq. Use phase dominates across all impact categories (e.g. 68.0% GHG emissions, 62.0% smog, 66.0% fossil resource use). Raw material extraction is the main contributor to water deprivation (30.0%) and mineral depletion (83.0%). Downstream processes account for 74.0% of total emissions.	Operation 68,0 %; Raw Material acquisition 23,0%
6	Volvo 7900 Electric [23]	0.00853	Most of the fossil climate impact comes from the operation phase due to electricity use (EU residual mix). Changing the grid mix greatly affects results: switching to Swedish grid lowers impact by ~69%, while hard coal mix nearly doubles emissions. Upstream also contributes, but less than operation.	Operation approx. 80%

ved for the Ebusco 3.0 (89.5%), which confirms the challenges related to the recovery of next-generation vehicle designs. These differences are particularly relevant in assessing compliance with circular economy principles – the higher the recovery rate, the lower the final environmental burden associated with vehicle disposal

These data were extracted directly from the interpretation sections of each Environmental Product Declaration (EPD) and provide deeper insight into the distribution of greenhouse gas (GHG) emissions across the value chain. Each analysis was conducted using the regional electricity mix applicable in Europe (typically the European residual mix), as defined in the respective EPDs, which ensures consistency in the assessment of the operation phase impact. Nevertheless, the study is subject to several methodological limitations. Since the data originate from EPDs prepared by different manufacturers, variations in databases, calculation tools, and methodological assumptions are inevitable. In particular, detailed information on energy use in battery production outside the EU is missing, as is data on non-CO_2 emissions, both of which may influence the overall environmental profile of vehicles. Furthermore, system boundaries are defined differently across individual declarations, limiting the comparability of results. The findings should therefore be considered approximate and interpreted with these constraints in mind.

Among the analysed models, Ebusco 3.0 shows the lowest total GHG emission at 0.00454 kg CO_2-eq/pkm, followed by Volvo 7900 Electric (0.00853 kg CO_2-eq/pkm) and Mercedes-Benz Citaro Hybrid (0.0111 kg CO_2-eq/pkm). The highest GHG emission is observed for the MAN Lion's City 12 C EfficientHybrid, with 0.0138 kg CO_2-eq/pkm, primarily due to the originally declared high lifetime mileage of 1.3 million km being adjusted to the standard 800,000 km used for comparability across models. This adjustment leads to a relatively higher impact per kilometer travelled.

In all cases, the operation phase is identified as the dominant contributor to total GHG emission, ranging from approximately 68% (Ebusco 3.0) to over 91% (Citaro Hybrid and MAN Lion's City). This phase includes the energy consumed during regular vehicle use and is highly dependent on the type and carbon intensity of the energy carrier used. In battery buses, the grid mix is key – for Volvo 7900 Electric, high emissions result from a fossil-heavy EU residual mix. Similarly, the Solaris Urbino 12 Hybrid and H2.City Gold confirms the dominant role of the operation phase, responsible for approximately 89.5% and 82.2%, respectively, of total GHG emissions per pkm.

The upstream phase, covering raw material acquisition, component production, and supply chain emissions, shows varying degrees of importance depending on drivetrain technology and material composition. In Ebusco 3.0, for instance, upstream emissions account for over 23% of the GHG emission, reflecting the embedded carbon intensity of advanced materials such as composite structures and high-capacity lithium-ion batteries, for the hydrogen-powered H2.City Gold, upstream contributions reach 16.7%, largely due to the production of fuel cell components and associated electronic systems. In contrast, hybrid vehicles generally show lower upstream shares (typically below 7%), which can be attributed to their more conventional material structure.

The core phase (vehicle assembly) and downstream processes (maintenance and end-of-life treatment) typically contribute the least to overall GHG emission. These stages generally account for less than 5% of total emissions, although in some electric bus models, battery replacements and associated maintenance activities may slightly increase the downstream share.

These findings reinforce the critical role of the use phase in determining the overall climate impact of public buses and underline the importance of energy source selection and grid decarbonization in reducing operational emissions. Electrified buses demonstrate considerable potential for GHG emission reduction. However, this potential can only be fully realized when combined with low-carbon electricity sources. Furthermore, the upstream burden of alternative drivetrains must be carefully considered, especially in battery-electric and fuel cell-electric vehicles, where material intensity, component complexity, and supply chain impacts contribute significantly to life cycle emissions.

4. Summary

This study presents a comprehensive review and environmental assessment of six models of urban buses equipped with alternative propulsion systems, based on data disclosed in verified Type III Environmental Product Declarations (EPDs) and interpreted in accordance with the Life Cycle Assessment (LCA) methodology. The analysis focuses on the comparative evaluation of manufacturer-declared environmental data, allowing for the identification of trends and dependencies relevant to the sustainable development of public transport systems. Such an approach enables an objective and standardized comparison of environmental performance across technologies, which is essential for informed policy-making and strategic fleet planning in the transition to low-carbon urban mobility.

It should be emphasized that the results presented in this study are based on secondary data reported in Environmental Product Declarations (EPDs) prepared by different manufacturers and analysts. As a consequence, they may vary in terms of methodological assumptions, databases applied, and calculation tools used, which inevitably affects the comparability of results. This is particularly evident in the case of electricity mixes. According to the Product Category Rules (PCR), the use of the European residual mix is recommended; however, individual EPDs adopt different approaches – for example, plant-specific data for Mercedes, Solaris, and MAN buses, the Portuguese mix applied to the production of H2.City Gold, or the Spanish mix considered for the air-conditioning operation of the same model. Such discrepancies may significantly influence the final results, especially with regard to greenhouse gas (GHG) emissions. Therefore, the outcomes should be interpreted with these limitations in mind and treated as an approximation of the actual.

Additionally, the review results should be interpreted with caution, as they rely on secondary data from EPDs prepared by different manufacturers and analysts. Variations in methodological assumptions, databases, and electricity mixes introduce uncertainties that may influence the final outcomes, meaning the findings represent indicative rather than strictly comparable values of the environmental impacts of the analyzed technologies.

The analysis revealed significant variations in environmental performance between the different drivetrain technologies. Battery-electric buses, despite higher environmental burdens during the production phase—mainly due to the use of lithium-ion batteries and advanced electronic systems – achieved the lowest GHG emission values across the entire life cycle. These results confirm the advantages of zero-emission vehicles in long-term environmental terms, especially when operational emissions are considered. Hybrid vehicles, which exhibited relatively higher emissions during the use phase due to partial reliance on combustion engines, demonstrated the highest potential for material recovery and recyclability, reaching up to 99%. This highlights their relative strength from a circular economy perspective, particularly in the context of end-of-life strategies. The hydrogen-powered bus occupied an intermediate position in terms of both life cycle emissions and end-of-life recovery potential, combining selected benefits of both technological approaches. Importantly, for all analyzed cases, the operational phase was identified as the dominant contributor to total GHG emission – accounting for 68–91% – which underscores the critical environmental significance of the use stage and the necessity of improving energy efficiency and reducing indirect emissions.

For zero-emission buses, the electricity mix is the decisive factor. The carbon intensity of electricity used to charge batteries or produce hydrogen (e.g., via electrolysis) directly affects environmental efficiency during the operational phase. It may significantly alter the comparative advantage of each technology depending on regional grid characteristics. In the EPDs reviewed in this study, an average European electricity mix was assumed, providing a representative and harmonized basis for comparison. Nevertheless, to fully realize the decarbonization potential of these technologies, transport fleets must be powered by electricity from low-emission sources – particularly renewables and nuclear energy. In this regard, the broader transformation of the energy system constitutes an essential element of any effective strategy aimed at reducing the environmental impact of modern public transport technologies. Without a parallel transition in energy generation, even the most advanced vehicle technologies cannot achieve their intended climate benefits.

The conclusions of this review are consistent with previous research. Nordelöf et al. (2019) compared the life cycle environmental performance of city buses powered by electricity, hydrogenated vegetable oil (HVO), and diesel, confirming the overall superiority of electric drivetrains in terms of total GHG emissions and underlining the pivotal role of the energy mix in shaping environmental outcomes [18]. These observations are further complemented by Regulski [19], who demonstrated that the optimal operational lifetime of city buses is typically in the range of 10–14 years, largely influenced by material durability and economic performance, which provides an important context for interpreting environmental outcomes. Similarly, recent life cycle analyses of alternative fuel buses [20] emphasize that material composition and energy pathways critically determine both environmental and economic efficiency. Taken together, these converging insights reinforce the validity of current EPD-based declarations and highlight their usefulness as a transparent tool for supporting sustainability-oriented decisions in urban transport planning.

In summary, the effective decarbonization of urban public transport requires a systemic, multidimensional approach that goes beyond the mere substitution of propulsion technologies. Parallel efforts must address energy supply decarbonization, ecodesign principles with end-of-life considerations, optimization of vehicle lifetime performance, and the implementation of transparent, standardized environmental reporting tools such as EPDs. Reducing urban transport's carbon footprint depends on a comprehensive strategy combining vehicles, energy systems, and operations.

Bibliography

[1] Burchart-Korol D, Jursova S, Folęga P, Korol J, Pustejovska P, Blaut A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. J Clean Prod. 2018;202:476-487. https://doi.org/10.1016/j.jclepro.2018.08.145

[2] CaetanoBus. Environmental Product Declaration: Bus H2.City Gold. Stockholm: EPD International AB; 2024 Jun 27. Report No.: EPD-IES-0015193. https://www.environdec.com/

[3] Daimler Buses GmbH. Environmental Product Declaration: Mercedes-Benz Citaro hybrid bus. Stockholm: EPD International AB; 2025 May 20. Report No.: EPD-IES-0022581. https://www.environdec.com/

[4] Ebusco BV. Environmental Product Declaration: Ebusco 3.0 12-meter. Stockholm: EPD International AB; 2024 Jul 8. Report No.: EPD-IES-0012607. https://www.environdec.com/

[5] EPD International. https://www.environdec.com (accessed on 2025 May 12).

[6] European Parliament, Council of the European Union. Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles. Off J Eur Union. 2009. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0033

[7] European Parliament, Council of the European Union. Regulation (EU) 2018/858 of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and repealing Directive 2007/46/EC. Off J Eur Union. 2018.

[8] Gabriel NR, Martin KK, Haslam SJ, Faile JC, Kamens RM, Gheewala SH. A comparative life cycle assessment of electric, compressed natural gas, and diesel buses in Thailand. J Clean Prod. 2021;315:128013. https://doi.org/10.1016/j.jclepro.2021.128013

[9] García A, Monsalve-Serrano J, Sari SL, Tripathi A. Life cycle CO_2 footprint reduction comparison of hybrid and electric buses for bus transit networks. Appl Energy. 2022;308: 118354. https://doi.org/10.1016/j.apenergy.2021.118354

[10] Gradin KT. Simplified life cycle assessment approaches and potential impact shifts. 2020. http://hig.diva-portal.org/smash/record.jsf?pid=diva2:1506681 (accessed on 2025 May 12).

[11] Iannuzzi L, Hilbert JA, Silva Lora EE. Life Cycle Assessment (LCA) for use on renewable sourced hydrogen fuel cell buses vs diesel engines buses in the city of Rosario, Argentina. Int J Hydrogen Energy. 2021;46(28):29694-29705. https://doi.org/10.1016/j.ijhydene.2021.01.065

[12] IK Ingenieria, Irizar Group, BYD Company Limited, Volvo Bussar AB, Daimler Buses GmbH, Ebusco BV, CaetanoBus, MAN Truck & Bus SE, TEMSA, Yutong Bus Co Ltd, Solaris Bus & Coach. PCR 2016:04 – Public and private passenger buses and coaches. Version 2.0.3. Stockholm. The International EPD® System.

[13] Lubecki A, Szczurowski J, Zarębska K. A comparative environmental Life Cycle Assessment study of hydrogen fuel, electricity and diesel fuel for public buses. Appl Energy. 2023;350:121766. https://doi.org/10.1016/j.apenergy.2023.121766

[14] International Organization for Standardization. ISO 14025:2006 – Environmental labels and declarations – Type III environmental declarations – Principles and procedures. Geneva: ISO; 2006.

[15] International Organization for Standardization. ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework. Geneva: ISO; 2006.

[16] International Organization for Standardization. ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: ISO; 2006

[17] MAN Truck & Bus SE. Environmental Product Declaration: Lion's City 12 EfficientHybrid. Stockholm: EPD International AB; 2022 Dec 15. Report No.: S-P-07585. https://www.environdec.com/

[18] Nordelöf A, Romare M, Tivander J. Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel. Transp Res Part D Transp Environ. 2019;75:211-222. https://doi.org/10.1016/j.trd.2019.08.019

[19] Regulski P. Assessment of the life cycle of city buses with diesel and electric drive in the operation phase. Combustion Engines. 2023;193(2):117-1212. https://doi.org/10.19206/CE-162108

[20] Regulski P. The material and economic assessment of the life cycle of city buses in the operational phase. Combustion Engines. 2023;192(1):50-54. https://doi.org/10.19206/CE-151942

[21] Solaris Bus & Coach sp. z o.o. Environmental Product Declaration: Solaris Urbino 12 hybrid bus. Stockholm: EPD International AB; 2022 Mar 31. Report No.: S-P-05600. https://www.environdec.com/

[22] Szczurowski J, Lubecki A, Bałys M, Brodawka E, Zarębska K. Life cycle assessment study on the public transport bus fleet electrification in the context of sustainable urban development strategy. Sci Total Environ. 2022;824:153872. https://doi.org/10.1016/j.scitotenv.2022.153872

[23] Volvo Bussar AB. Environmental Product Declaration: Volvo 7900 Electric. Stockholm: EPD International AB; 2023 Nov 2. Report No.: S-P-11237. https://www.environdec.com/

Iga Przytuła, MEng. – Faculty of Transport and Aviation Engineering, Silesian University of Technology, Poland.

e-mail: *iga.przytula@polsl.pl*

Prof. Dorota Burchart, DSc., DEng. – Faculty of Transport and Aviation Engineering, Silesian University of Technology, Poland.

e-mail: *dorota.burchat@polsl.pl*