

Zero-Emission Buses for Public Transport

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1. Buses for Public Transport—Leading Heavy-Duty Vehicle Electrification

Buses for public transport have a unique role to play in the decarbonisation of the road transport sector. With known and scheduled routes, large and cost-sensitive fleets, heavy passenger loading, long hours of operation, and stringent air pollution regulations in the metropolitan areas where most of these vehicles are located, bus decarbonisation faces unique challenges. Buses are also subject to tighter regulations as part of competitive tendering processes by local and regional governments aiming to decarbonise public transport.

The ongoing transition to zero-emission buses presents opportunities for innovation across several aspects of bus infrastructure and system planning, including bus powertrains, energy storage systems, charging and fuelling infrastructure, thermal management systems for buses, routing and route-planning, trip demand prediction, traffic signal operation integration, environmental aspects, business models, and technical standards.

Based on the IEA's (International Energy Agency) Global EV database [1], the global stock share of electric buses (including battery electric, plug-in hybrid electric and fuel cell electric) has been showing steady growth in the last decade and is just under 5% (until 2024). While not as high as two- and three-wheelers (around 9%), the electrification of buses is slightly further along than passenger vehicles (around 4.5%) and well ahead of trucks (<1%). As such, buses are amongst the leading vehicle segments in electrification globally and the undisputed leader amongst heavy-duty vehicles.

In this Special Issue on zero-emission buses for public transport, we describe the state-of-the-art of zero-emission buses from around the world. The articles cover a wide range of different techno-economic contexts, including bus-retrofitting in Thailand, techno-economic analyses in Lebanon, total cost of ownership (TCO) estimates across Europe, feasibility studies for electrification of bus operations in rural Croatia and feasibility and decision-making tools for electric Bus Rapid Transit (eBRT) systems. We also cover simulation of bus operations and improved methods for energy-use prediction, both of which are critical for efficient and economic electric bus deployment.

The technical and economic choices made, the frameworks of design, planning and operation and the requirements for capacity-building, research and knowledge development of these first 5% of electrified buses offer many lessons, not just for the remaining 95% of buses yet to be decarbonised, but also for other heavy-duty sectors: trucks for urban and regional deliveries, coaches for intercity passenger transport, long-haul trucks and further along, vehicles for use in the construction, agricultural and mining sectors. With



Received: 25 February 2026

Accepted: 6 March 2026

Published: 18 March 2026

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this Special Issue, we hope to share knowledge, encourage international engagement, and accelerate this ongoing transition to zero-emission transportation.

2. Findings from the Special Issue

The findings range from initial feasibility checks to more advanced performance optimisation associated with mature ongoing electric bus operations. Feasibility assessments form the initial basis for planning electric bus operations.

Initial steps often include retrofitting of standard Internal Combustion Engine (ICE) buses. As an example, Janjamraj et al. [2] propose a methodology and practical learnings from the conversion of standard ICE buses into electric buses. This is provided in the context of Thailand where pollution, investment in electric buses and the availability of qualified personnel are critical issues. Overall, the study enabled the training of relevant personnel to support the conversion of standard ICE buses into electric buses and attend to their maintenance.

Battery electric buses are typically introduced in fleets that also include other alternative fuels and powertrains like compressed natural gas (CNG) and hybrid buses, as described by Haddad and Mansour [3] in Lebanon. The study compares the operation of various powertrains in real conditions in Lebanon, covering a range of traffic conditions. The results show that the use of electric buses is most beneficial when sufficient charging infrastructure and BRT lines are available. However, at this stage, a balanced mix of technologies is advised for developing countries.

Along with bus operations, BRT systems are also increasingly being considered as a cost-effective option for mass transit with high service quality. For integration with urban infrastructure, BRT systems require alignment of many stakeholders and careful selection of routes.

Delialis et al. [4] develop a Decision Support framework, a digital tool for analysing demand and mobility patterns, corridor attributes, traffic and environmental parameters and identifying priority eBRT corridors. The framework applies a previously developed machine learning model, XGBoost, on data from 28 key corridors in Athens, Greece, and aims to assess the feasibility and viability of eBRT corridors.

Morfoulaki et al. [5] apply an ex-ante methodology for assessing the social impact of in-vehicle and out-of-vehicle innovations in eBRT systems. Expert and stakeholder feedback are used to identify innovations with strong social impact, compare their alignment with societal needs, and offer guidance for strong embedding of future eBRT systems within a social context.

In addition to alignment with urban context and societal/passenger needs, electrification can involve a large number of stakeholders across national, regional and local government as well as the private sector. The case described by Thilakhan et al. [6] is instructive. They provide an in-depth case study of the stakeholders and the decision-making processes involved in the deployment of electric buses in Sri Lanka. The study highlights the political economy factors, institutional fragmentation, and socio-cultural resistance. It also develops a series of recommendations to navigate towards successful electric bus deployment: innovative financing, public engagement and pursuit of global funding opportunities, calling for a comprehensive Sri Lankan national plan on electric buses.

Further along, cost analyses and deployment strategy form the basis for successful implementation. Barragan-Escandon et al. [7] evaluate the most suitable bus deployment strategy for the city of Cuenca in Ecuador, considering technical, economic, social and environmental criteria. They find that the most critical factor is the passenger capacity but the selected deployment scheme results in a beneficial long-term investment. Overall,

the study methodology is replicable to feasibility studies on electric bus deployment in other cities.

Ghotge et al. [8] present an overview of the total cost of ownership (TCO) of battery electric buses across Europe (the EU27 + UK + Türkiye). A comprehensive review of the assumptions and data used for the TCO calculation of buses in the current literature is provided and the calculated TCO is compared with diesel costs in each country to identify the countries in which bus electrification is financially most competitive.

Šoštarić et al. [9] compare the implementation of electric and diesel buses for public transport services in a low-density area of the city of Jastrebarsko, Croatia. The comparison is based on both direct and indirect costs, covering vehicle acquisition, operation, charging, maintenance, and environmental impacts during the lifecycle of the buses. The authors highlight both the economic challenges of running electric bus operations in low-density rural areas and point to the need for targeted support for rural areas where public transport services play a critical role in ensuring equitable opportunity and access and have very high societal value.

In more mature markets, once electric buses have been deployed, operator capacity is developed and costs of operation are known, optimisation of performance and cost reduction are the next objectives.

Klaproth et al. [10] investigate the impact of energy consumption and charging behaviour on battery ageing for urban electric buses. Based on results from real-world data, they propose an optimised operational strategy based on state of charge, range, vehicle idle time and charging power, and assess the actual reduction in battery ageing and how far this could be realistically implemented in cities.

Heide et al. [11] present an open-source simulation framework to assess the deployment of electric bus fleets from a system-level perspective. Indicators such as energy consumption, battery ageing, smart charging, charger location, etc., are considered. This is applied specifically to Berlin's bus network with the evaluation of three scenarios, clearly highlighting the trade-off between infrastructure requirements, fleet size and operational efficiency.

Zhao et al. [12] propose a methodology for accurate prediction of electric buses' energy consumption. They use a Light Gradient-Boosting Machine (LightGBM) framework which incorporates temporal, weather and driving pattern features and can be used for real-time Internet of Things (IoT) applications. The prediction shows lower error compared to conventional methods, making it suitable for further optimisation of electric bus operations.

In addition to standard electric buses, trolleybuses should also be included among design choices. Von Kleist and Lehman [13] use real-world data to develop a simulation of hybrid trolleybus (i.e., trolleybuses with traction batteries) operations for the purpose of investigating battery ageing and peak grid loads. The results describe a trade-off between the benefits of slower battery ageing through per-vehicle load flattening over the time connected to the catenary with the benefit of collective peak reduction through fleet-level scheduling.

3. Concluding Remarks

This Special Issue provides a comprehensive overview of current developments regarding zero-emission electric buses for public transport within the context of the ongoing transition towards decarbonised mobility. The contributions include feasibility studies, deployment plans, cost and lifecycle assessments, and advanced operational optimisation in more mature markets. Together, they show that bus electrification is increasingly considered in strategic transport planning, and involves a systemic transformation across

infrastructure planning, grid integration, economic models, stakeholder coordination, workforce development and social acceptance.

Across the publications in this Special Issue, several conclusions can be drawn: feasibility and cost-effectiveness are highly context-specific, yet interesting frameworks are proposed for replication; the TCO is improving but remains sensitive to local conditions and policy support, and therefore the optimisation of infrastructure planning and operation is required; digital tools and data-driven methods significantly enhance planning and operational efficiency; and stakeholder alignment and regulations are decisive for successful implementation.

Looking ahead, the next phase requires scaling from partial deployment in specific cities to a comprehensive and global fleet electrification. This requires integrated planning of charging infrastructure and power systems, greater standardisation and interoperability, continued development of smart charging and battery lifetime management strategies, and stronger institutional and technical capacity. Attention to battery lifecycle management, circularity and sustainable supply chains will also become increasingly important as fleets expand. The experience gained from bus electrification provides valuable lessons for future decarbonisation of buses as well as other heavy-duty vehicles.

Author Contributions: Conceptualisation, R.G. and T.G.; writing—original draft preparation, R.G. and T.G.; writing—review and editing, O.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Horizon project, eBRT2030 (<https://ebrt2030.eu/>) under project number 101095882.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

eBRT	Electric Bus Rapid Transit
CNG	Compressed Natural Gas
EU27	27 Member states of the European Union
EV	Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IoT	Internet of Things
LightGBM	Light Gradient-Boosting Machine
SoC	State of Charge
TCO	Total Cost of Ownership
UK	United Kingdom

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