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Research article

Comparative analysis of decarbonization of local public transportation: A real case study

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ABSTRACT

Climate disruptions have prompted institutions to invest in zero-emissions technologies, in recent years. As a result, the transportation sector has witnessed a shift from internal combustion engines to electric. Several public transport companies have initiated the "Zero-emissions" project to introduce alternatives to diesel in their bus service. This paper delves into the impacts of transitioning from diesel-powered to electric buses. It starts by estimating emissions produced by buses and comparing them. Subsequently, the analysis evaluates the implications of renewing the fleet on the service, considering the change in bus capacity. Additionally, a profitability analysis assesses the Total Cost of Ownership, factoring in helpful life and average distance (kilometres) driven annually. Overall, the findings indicate that switching to electric buses is a promising approach towards achieving environmental objectives. The study shows that investing in electric buses, particularly those measuring 9-m, offers significant economic benefits while aligning with sustainability goals. The research demonstrates that electric buses yield a substantial reduction in global and local emissions when compared to their diesel counterparts. Adopting a comprehensive "well-to-wheel" perspective, electric buses achieve an impressive 68 % reduction in emissions. However, concerning local emissions, certain specific lines recorded values exceeded legal limits. While the initial investment costs for electric buses may surpass diesel buses, the total cost of ownership analysis conducted over 15 years indicates that electric buses can become more cost-effective over time. This cost-effectiveness and their environmental advantages strengthen the case for adopting electric buses to pursue sustainable transportation systems.

1. Introduction

The massive increase of the global population (9.7 billion by 2050) [1] and its concentration in urban areas (70 % by 2050) [2,3] will produce a rise in air pollution, noise pollution, need of infrastructures and energy [4,5]. This change will contribute to global warming, a practical problem widely discussed in the literature. The study [6] proposed different models that forecast the number of days per year with temperature over 32 °C (in 2070, the models predicted 46 days above 32 °C while the more pessimistic ones indicated 60 days). The main reason for climate change is the Greenhouse Gasses (GHGs) emissions composed of carbon dioxide and methane that have grown by 47 % and 156 % since 1750 [7,8]. The reduction of GHGs has become a priority of the Conferences of Parties (COP), and they have set the target of reducing global GHGs emissions by 55 % (compared to 1990) in 2030 and carbon

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neutrality for 2050 [9]. But nowadays, how much the transport sector influences GHGs emissions? Given the study by the United States Environmental Protection Agency (EPA), the transport systems contribute for 29 % of CO_2 [10]. Transportation sector, thus, has a strong potential to decrease its GHGs emissions. Coppola in his study for the National Association of Travel Carriers) [ANAV], cite the European Union [EU] Statistical pocketbook which says that 31 % of the CO_2 equivalent emissions come from the transportation system. Regarding Italy the 25 % of the GHG come from the transport sector, 93 % of which arises from the road-based transport and of this 93 % the GHGs buses share is 3 % [11]. To reduce the impact of GHGs, governments and international organizations have produced many regulations and have started to invest in this field. The EU, also due to the Covid-19 crisis, has promoted the Next Generation Europe Union (NGEU) [12], an 800 billion € investments plan that focuses on the ecological and digital transition. This plan provides resources for Italy's national program, "National Recovery and Resilience Plan" (NRRP) [13] which consists of 191.5 bn € [14]. This mission aims to help to reach the decarbonization objectives. The first investment line wants to go forward with renewable energy. Following this objective and embracing renewable energy, which has maintained in the years its characteristic problem of discontinuity, the second line of investment provides resources to empower and digitalize the electric grid. Then the third line discusses the European target of increasing the usage of hydrogen for transport and the industrial sector. The fourth line of investment deals the local transportation with two purposes: decarbonization and improving the quality of life.

This paper focuses on decarbonizing transport vehicles; the NRRP's M2 mission provides resources for renovating the bus fleets from Internal Combustion Engine Vehicles (ICEV) to Battery Electric Vehicles (BEV). The NRRP follows the previous National Strategic Plan for Sustainable Mobility that aims to put in force the transition toward sustainable mobility. This research primarily concentrates on electric propulsion systems utilized in buses, and additionally, it explores the potential benefits and challenges associated with their wider implementation. Regarding environmental impact, electric buses drastically reduced local emissions to virtually zero [15]. This is because, unlike traditional vehicles, they do not rely on the combustion of fossil fuels for locomotion. The primary challenge to be tackled is the limited range of electric vehicles. However, recent advancements in battery technology suggest that this approach may be the most viable solution in the mid to long-term timeframe. The recent advancement of lithium batteries, which possess a higher energy density, along with the capacity for high-power recharging, has overturned a positive outlook among mobility stakeholders regarding this technology [16]. Thanks to these advancements, the primary issue of range limitations with Electric Vehicles (EVs) is beginning to be effectively addressed.

The main contributions of this study include providing a comprehensive and comparative analysis of the transition from conventional diesel-powered buses to electric buses within public transportation systems. The study addresses various aspects, ranging from environmental impact to economic feasibility and social sustainability, and can be summarized in the following points.

1. This study conducts an in-depth analysis of the environmental impact of e-buses compared to diesel buses, through a well-to-wheel approach.
2. The work evaluates the Total Cost of Ownership (TCO) of e-buses over a 15-year period. It considers various cost factors, including initial investment costs, maintenance expenses, and potential government incentives.
3. It conducts a profitability analysis to determine the minimum number of kilometers required for e-buses to be more economical than diesel buses. By considering different scenarios, such as varying the average distance covered by the buses and comparing maintenance costs, the researchers identify the conditions under which investment in e-buses becomes more advantageous.
4. This research emphasizes the importance of charging infrastructure for the successful operation of e-buses. Lastly, the work addresses the social sustainability aspects of adopting e-buses. It highlights potential changes in bus capacity, schedules, and seating arrangements, which may impact passenger satisfaction and overall acceptance of e-bus systems.

Overall, the topic covered in this study is crucial for informing future policy decisions, guiding investment in public transportation, and promoting the adoption of more sustainable and innovative technologies to create greener and more habitable cities for future generations. The main contributions of this article lie in its in-depth assessment of the environmental, social, and economic aspects of the transition from diesel to electric buses. The study provides valuable information for policymakers, transportation operators and stakeholders involved in shaping sustainable and environmentally friendly public transportation systems. It also recognizes that the transition to electric buses may have social and economic implications, such as changes in bus capacity, schedules, and passenger satisfaction. These issues must be considered to ensure successful implementation. Addressing the urgent need for cleaner transportation solutions, the article contributes to ongoing efforts to combat climate change and improve air quality in urban areas.

The remainder of this paper is organized as follows: the next Section 2 presents a literature review that aims to examine the main studies associated with the electric transition in local public transport. Section 3 explains the methodology used to assess the impact of the renewal of the bus fleet from ICEV to BEV. Section 4 highlights the technical characteristics of the case study considered in work. Subsequently, in Section 5, the results obtained from several scenarios are discussed. Finally, the paper is concluded in Section 6.

Nomenclature	
km	Kilometers per year
km_0	Kilometres per year made to cover the investment.
$C_{bus}(km_0)$	Bus's kilometric purchasing cost
$F(km_0)$	Bus's kilometric government incentive
$C_r(km_0)$	Bus's revamping/components substitution kilometric cost
$C_t(km)$	Traction kilometric cost
$C_m(km)$	Maintenance kilometric cost

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$C_i(km)$	Kilometric infrastructure cost
$C_{bus}(T_n)$	Bus's yearly cost depreciation
$F(T_n)$	Bus's yearly fee depreciation
$C_m(T_n)$	Maintenance cost.
$C_a(T_n)$	Adblue cost. Given by annual kilometers multiplied by the kilometric cost of Adblue
$C_r(T_n)$	Bus's revamping cost depreciation.
$C_w(T_n)$	Tire full-service cost
$C_{fuel}(T_n)$	Fuel cost
$km(T_n)$	Annual kilometers

2. Literature review

The transition from diesel to electric buses in the Local Public Transport (LPT) sector is a topic of great importance in the context of decarbonization. This literature review aims to examine the main studies and research conducted on this topic to provide an overview of the challenges, benefits, and best practices associated with local public transport. Most of the research is driven by increasing market penetration of EVs and focusing on the distribution of charging stations [49]. The combination of bus battery and charging infrastructure requires reliable power to maintain stable operation even under extreme conditions. Ref. [17] presents a Mixed-Integer Non-Linear (MINLP) [18] optimization approach for optimal placing and sizing of the fast-charging stations. Station development costs, EV outages, grid outages as well as the location of power substations and city roads are some of the factors included in the proposed approach. The authors in Ref. [19] developed a mixed integer linear optimization model is developed to determine the minimum number and location of required charging stations for a bus network while respecting operational and technology related constraints.

Compared with local public transport, the transition from diesel buses to electric buses offers numerous environmental advantages. Electric buses have zero emissions during use, contributing to the reduction of GHGs emissions and improving air quality in urban areas, as the authors have demonstrated in Ref. [20]. Ref. [21] highlights the potential impact of several options for decarbonizing public bus transport. An optimization model is used to estimate the associated carbon emissions, using a life cycle perspective and various implementation scenarios. Similar work [22] is being done in China, where it is recognized that completely replacing all diesel buses with electric Buses may not be feasible due to budget constraints. Therefore, the goal is to find an optimal solution, called “fleet deployment equilibrium strategy”, which takes into account the spatial and temporal fluctuations of passenger flows in the various bus lines.

In addition to environmental performance, researchers have discussed the lifecycle costs of several types of transit buses. Ref [23] proposes a new cost-benefit method for planning electric city bus vehicles on a single route. This article provides a detailed overview of the various performance characteristics of three categories of electric buses. The economic, operational, energetic, and ecological properties of each technology are checked in detail using simulation models and operational data. The authors in Ref. [24] develop a Life Cycle Cost (LCC) model that provides empirical LCC results. This model is used to predict possible scenarios based on cost estimates for next-generation technologies. The study concluded that diesel buses have the lowest TCO. The TCO of an electric bus has been found to be approximately 10 % higher than that of a conventional diesel bus [25]. It has been demonstrated in numerous studies that electric buses bring greater benefits in terms of energy efficiency compared to traditional diesel and hybrid electric buses. Ref. [26] provides a detailed overview of the various performance characteristics of three categories of electric buses: hybrid, fuel cell, and battery. The economic, operational, energetic, and environmental properties of each technology are examined in detail using simulation models and operational data presented by different scientists in different situations [27,28]. In addition, the authors in Ref. [29], showed a comparative analysis of energy and environmental performance, across four types of urban passenger bus powertrains, including diesel and electric, within the framework of Well-to-Wheel (WTW). They found that EVs clearly outperformed in the tank-to-wheel transition phase, however, actions to improve energy efficiency and the environment should focus on how to generate clean energy in the electrical mixture and by what technology. Finally, the electric motor is highly efficient thanks to the contribution of the effective functioning of the regenerative braking systems used by the electric bus [30].

This study significantly contributes to the existing literature by offering a more extensive and comparative analysis that surpasses the conventional focus on the environmental advantages of electric buses. The literature review reveals a notable gap in research, particularly concerning a comprehensive examination and comparison between diesel and electric buses within a specific regional or urban context. While numerous studies concentrate on the environmental benefits of electric buses in contrast to their diesel counterparts, there exists a dearth of research investigating the economic facets, operational considerations, and local nuances associated with the implementation of electric buses in a particular urban setting. This paper strives to fill these gaps in the literature by presenting a meticulous and data-driven analysis of the transition from diesel to electric buses within a specific region. It not only considers the environmental implications but also delves into the economic viability and practicality of adopting electric buses in the real-world scenario of a particular city or urban area. By offering a more holistic perspective, this study aims to enhance our understanding of the broader implications and challenges associated with the transition to electric buses, contributing valuable insights for policymakers, researchers, and stakeholders involved in sustainable urban transportation planning.

3. Methodology

This Section outlines the methodology employed to evaluate the impact of transitioning the bus fleet from ICEVs to BEVs. The assessment draws upon the Zero Emissions project in Pavia and sets up a comparative analysis between two distinct scenarios: the current situation utilizing diesel-powered buses for Pavia's urban service and a future scenario with EVs. The comparison is made over the most passenger-dense period, which spans from September to June. Additionally, this comparison takes into account various factors such as the total operating costs, emissions, and the overall reliability and performance of both types of vehicles under different operating conditions. The developed model is structured as follows.

- Kilometers allocation to bus and working shift.
- Energy consumption per bus is further allocated to each line considered.
- Global and local emissions per bus further allocated to each line considered.
- The occupancy of the lines, based on the average people climbed and the average people on board. The objective of this phase is to identify any possible criticality of the future service that may derive from the renewal of buses, especially in terms of vehicles' available capacity.
- Finally, two profitability analyses are based on the computation of the TCO, which represents the cost that the company has to sustain when owning a certain technology. These profitability analyses consider two sub-scenarios regarding the electric main one: the maintenance equal for electric and diesel buses and the decrease in maintenance cost for electric buses.

3.1. The procedure

Initially, it is essential to assign the distance covered by each bus to its respective route during the considered period; the Python programming language has been utilized to facilitate this task. Furthermore, this method aids in detailed tracking and analysis, allowing for the assessment of each bus's efficiency and utilization within the transportation network. Fig. 1 resents the operations performed by the proposed method. The procedure begins by reading the file that includes a matrix detailing bus shifts as rows, the days of the period as columns, and the company bus numbers as matrix elements. These numbers denote which bus is assigned to a specific shift on a particular day. Building upon this, it is feasible to construct a data frame with the company bus numbers as rows and bus shifts as columns. This frame counts the instances of a certain bus on a specific shift and, consequently, on a particular route. The program written in Python then reads another file that contains the number of kilometres each bus shift travels. It then integrates this information with the aforementioned data frame. This integration is achieved by multiplying the instances of each shift by the corresponding shift length, thereby calculating the total kilometres each bus shift covers during the period. By incorporating this process, it is possible to develop a comprehensive view of the utilization and efficiency of each bus, assisting in further optimization of the transit system.

The total number of kilometres could have been computed simply by counting the number of the days of the period considered and multiplying it for the kilometres of each bus shift; however, if this method was followed, it could not have been possible to highlight the

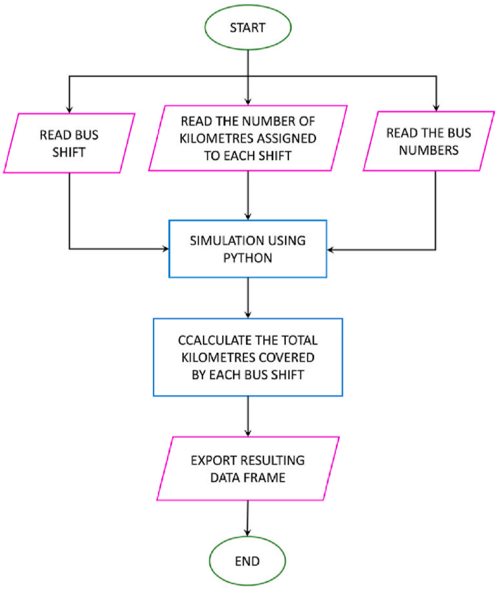


Fig. 1. Flow Chart for kilometres allocation to bus and machine shift.

kilometres made by each bus, which is a crucial information for the following analysis to allocate consumption, emissions and costs to each line.

An important additional factor to consider concerning bus shifts is the utilization of backup buses to replace those that break down during service. This study does not account for these substitutes under the presumption that the regular service operates strictly as scheduled, without any unplanned interruptions or breakdowns.

3.2. Energy consumption

Regarding the diesel busses, considering the kilometres covered by each bus during the time span used for the analysis and having extracted the respective injection of fuel in liters to provide the service from the management software, it is computed the average fuel consumption in l/km for each bus considered and for each line, after converted, through the diesel Lower Heating Value (LHV), in MJ/km. It is crucial as well to visualize the total amount of MJ used to carry out the service during the period of the analysis as it is going to be used in the later steps. Regarding the electric scenario, given the average kilometric consumption of the IVECO buses, from tenders' documentation, the same methodology has been used to obtain the absolute amount of MJ necessary to provide the forecasted service.

3.3. Local and global emissions

Given the EURO VI standard emissions rate [31] of Particulate Matter (PM), Carbon Monoxide (CO), and Nitrogen Oxides (NO_x), in g/km, it is possible to find the local emissions allocated to each line. First, by having the total number of kilometres of the lines, the total grams of pollutants related to each bus line are computed for the period considered. After acquiring the aforementioned data, the algorithm calculates the number of pollutants emitted per line during a typical day of service, measured in grams per day (g/day). Naturally, in the case of the electric scenario, the local emissions are reduced to zero. Concerning the global emissions of GHGs, it is fundamental to consider a Well-To-Tank (WTT) approach [32,33], thus considering the production, transportation, and distribution of diesel and the production, transmission and distribution of electricity. Regarding only the diesel scenario, the Tank-To-Wheel (TTW) [34] approach had to be considered as well, and it used the (gCO_2eq/MJ_{diesel}) from the combustion of the fuel in ICEs. Knowing the kilometric consumption of each line for both scenarios, it is possible to calculate the kilometric equivalent grams of CO_2 emitted on each line. Therefore, the WTW analysis is just performed for the diesel scenario, and as shown Fig. 2 [29], the analysis is combined the WTT and TTW results and adds the consumptions and emissions given in each step. Then the energy, fuel, and emissions for the WTT step are calculated and added to the fuel usage for the TTW step. The study evaluates emissions from electric vehicles during the WTT phase by considering the diverse sources that contribute to electricity generation in Italy, known as the Italian energy mix. This mix encompasses both renewable (e.g., solar, wind, hydro) and non-renewable (e.g., fossil fuels like coal, natural gas) sources. By utilizing the current Italian energy mix, the study provides a practical and context-specific assessment of the emissions linked to charging electric vehicles.

3.4. Output

The calculated global emissions help quantify the potential reduction in carbon dioxide levels, an important aspect that aligns with the GHG reduction objectives outlined in Section I. Initially, the primary aim regarding local emissions is to assess the impact of this transition on Pavia's air quality, utilizing data from Lombardy's Regional Environmental Protection Agency (ARPA) [35]. However, the resulting impact was found to be minimal and, therefore, negligible. Consequently, the analysis has been confined to understanding the reduction impact on the local emissions of the Public Transport Company's fleet in Pavia.

3.5. Consequences on service

The transition from diesel-powered buses to EVs will decrease the number of available seats onboard. This change will thus

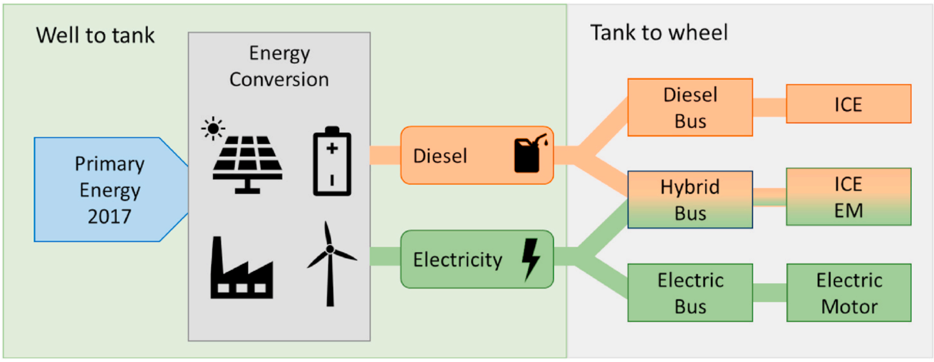


Fig. 2. WTW analysis diagram.

influence the service from the standpoint of seat availability, necessitating a reassessment of potential service modifications. The collected data has been categorized into different time slots, each spanning 3 h, with the start of service (SOS) set at 6 a.m. and the end of service (EOS) at 8 p.m. Subsequently, for each ride, the average number of passengers that boarded and the average number of passengers onboard were computed. After filtering the data, the occupancy percentage was determined as the ratio between the average passengers onboard and the bus's seating capacity. The same operation was repeated for the average number of passengers that boarded. In the final step, segregated into the aforementioned daytime zones, the rides were visualized using boxplots to clearly represent bus occupancy during different periods of the day [36].

In this study, the use of boxplot visualizations enables a detailed depiction of the distribution of different rides occurring at the same time. In the selected case study, it is beneficial to visualize ride occupancy for each daytime period. This visualization technique facilitates the identification of peak service hours and potential bottlenecks. Outliers in this context signify rides that are either overcrowded or underutilized compared to the majority. Rather than being erroneous data points, these outliers allow us to identify specific runs that may need to be modified or possibly eliminated, typically underutilized, to accommodate overcrowded routes better.

3.6. Profitability analysis

The cost analysis described in this study is a profitability analysis for calculating the TCO of different types of buses over their lifespan. The analysis is executed by considering various cost components over a specific period (typically the lifespan of the bus) and summing them up to calculate the TCO for each year. The analysis considers different cost elements, such as purchasing, incentives, maintenance, infrastructure, fuel, and other relevant expenses. Two profitability analyses were conducted to evaluate the potential of the service to generate profits exceeding its expenses. These analyses were based on the calculation of the Total Cost of Ownership (TCO).

- The profitability of investment was evaluated under two primary scenarios: the electric scenario, considering 12-m and 9-m electric buses, and the diesel scenario, factoring in 12-m and 7-m diesel buses. These profitability assessments were carried out over a span of 15 years (1).
- Profitability of the investment considering one year of ordinary exercise, the previously mentioned four types of buses during one of their years of life and the variation of the average number of kilometers made by a single bus in a year to better understand the entity of the spreading of costs on the units of product (2).

Both the profitability analysis is repeated for the two electric sub-scenarios and are based on the following formulas that consider kilometric costs in €/km, which means that all the costs that were considered for the analysis, are assigned to the buses with the distance as the allocation base in order to understand how much the technology cost per kilomiter for the company.

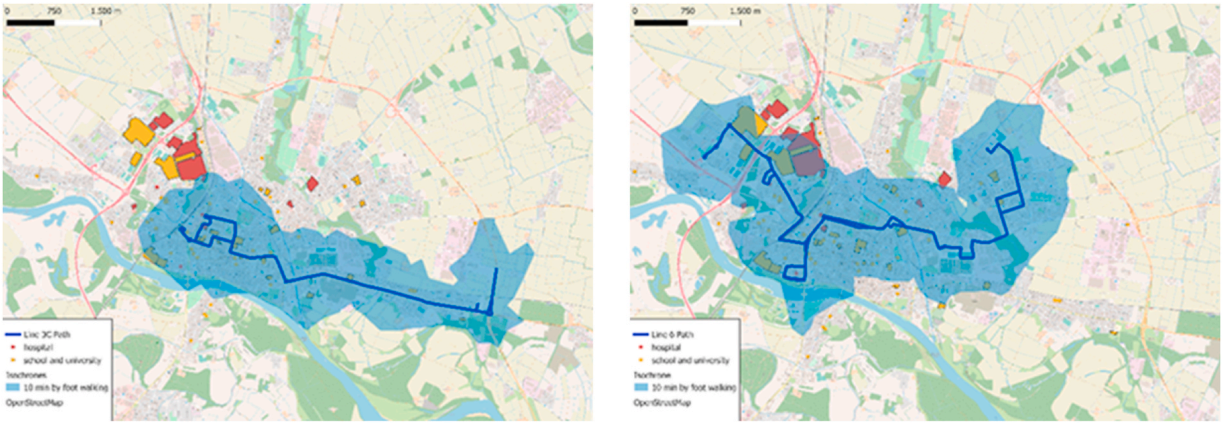
The formula (1) utilized for the first of the two profitability analyses, which is employed to calculate the TCO, is as follows:

$$TCO(km) = \frac{(C_{bus}(km_0) + F(km_0) + C_r(km_0)) \bullet km_0}{km} + C_t(km) + C_m(km) + \frac{C_i(km)}{km} \bullet km_0 \tag{1}$$

The variation in time of TCO is computed as shown in (2), with T_n being a generic year of the bus life.

$$TCO(T_n) = \frac{C_{bus}(T_n) - F(T_n)}{km(T_n)} + \frac{(C_{bus}(T_n) - F(T_n)) + \left(C_m(T_n) + C_a(T_n) + C_r(T_n) + C_w(T_n) + C_{fuel}(T_n)\right)}{km(T_n)} \tag{2}$$

The key objective of both profitability analyses is to determine the cost-effectiveness and profitability of using electric buses



(a) Line 3C of Pavia's urban service. (b) Line 6 of Pavia's urban service.

Fig. 3. Lines of Pavia's urban service.

compared to diesel buses. The focus is on understanding how much the technology costs per kilomiter for the transportation company. By calculating the TCO over the lifespan of the buses and for specific years of their operation, the analysis helps in making informed decisions about the most sustainable and economically viable option for the urban service. This detailed analysis is crucial for public transportation agencies and decision-makers to make informed choices that align with long-term sustainability and financial viability goals.

4. Case study

A collective transport company operating in the provinces of Pavia, Bologna, Bergamo, Monza, South-East Milan, and Crema (through its affiliate, Miobus) is participating in the "Zero Emissions" project. This collective includes Transportation Company Novarese (STN), Dolomiti Bus, and Venetiana, each offering bus services in the provinces of Novara, Torino, and Trentino Alto Adige, respectively (See Fig. 3). At present, the group possesses over 1200 buses, with direct ownership of 772 units, which have an average age of eight years. Of these, 97.5 % are powered by diesel engines, 2 % are hybrid vehicles, and the remaining 0.5 % operate on compressed natural gas.

4.1. Zero emissions project

The Zero Emissions project has the aim of renewing Pavia's urban fleet from diesel-powered buses to electric ones. The NRRP will cover 80 % of the investment while the remaining part will be covered by the LPT company, which will be able to ask for a prorogation of the contract of service as allowed by the regulation [37]. The renovation of the fleet is going to be implemented first on 2 of the 15 lines of the urban service, Line 3C (Fig. 3a) and Line 6 (Fig. 3b). Line 3c is the most critical line as it passes directly through the historical city center, where the space for manoeuvres is extremely limited. It is 6.5 km long and the average time of the most common type of ride is 26 min. While Line 6 is still a line that connects the eastern part with the western part of Pavia, but it has a deviation that touches the northern bank of the river Ticino. It covers 10.3 km, and the average time of ride is 45 min.

Particular attention has been given to the choice between the several types of charging already in commerce: opportunity and overnight [38]. Opportunity charging involves at least one infrastructure along the bus route, and it is often referred to as "on-route charging" or "fast charging." This method enables a bus to charge during its operational shift without needing to return to the depot. On the other hand, overnight charging, as the name suggests, involves assessing the vehicle once it has returned to the depot after completing its shift, typically during evening or night hours. Overnight charging is generally slower compared to opportunity charging, as it occurs when the buses have concluded their operational shifts. Consequently, high-capacity batteries are necessary to ensure sufficient autonomy for the buses. Due to the higher costs associated with opportunity charging, the decision was made to opt for overnight charging. To secure resources from the NRRP, a public transport company initiated two separate tenders for the charging infrastructures and the electric buses, respectively. The tenders have been won by Enel-X [39] for the infrastructures and IVECO [40] for the two types of buses. The buses are produced by IVECO with the name E-way and are of two types: 12-m and 9-m [41] both plug-in in compliance with the overnight charging choice. The parameters of the urban passenger buses and their values are listed on Table 1.

These electric buses have the same equipment; thus, they are equipped with the same Alternative Current (AC) Permanent Magnet Motor (PEM) [42], but they differ in the number of batteries. The project will use charging stations of 150 kW and will charge a maximum of two buses each. The project will change the organization of Pavia's depot, making it also an essential structure for future tenders. Enel-X produces the selected charger with the commercial name of Juice-Pump 150 [43] that uses Direct Current (DC) and has two CCS2 connectors [44–46]. According to the technical specifications provided by Enel-X, the charger will allow a voltage of 1000 V, a current of 200 A, and a maximum power of 150 kW.

5. Results and discussion

This section will present and compare the results achieved in line with the analysis objectives. Foremost, it is crucial to determine the total kilometers travelled by each bus line during the period from September to June. As depicted in Fig. 4, lines 1 and 3 received

Table 1
Electric buses parameters.

Parameter	9 m	12 m	Unit
Total places	56	77	–
Gross Vehicle Mass	14	19	t
Number of batteries	6	10	–
Battery nominal voltage	644	644	V
Battery nominal energy	42.5	42.5	kWh
Total battery capacity	255	425	kWh
Type of motor	AC PEM	AC PEM	–
PEM continuative power	116	116	kW
PEM maximum power	160	160	kW
Regenerative breaking energy	0.61	0.61	kWh

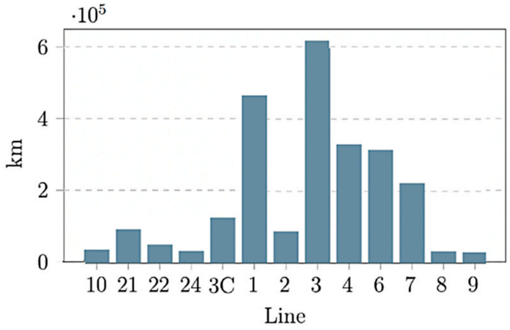


Fig. 4. Total kilometres for each line, September–June period.

the most service from the public transport company during the period, boasting the highest number of daily bus shifts and rides. Lines 6 and 3c, which are the initial lines to be impacted by the Zero Emissions project, can be characterized as intermediary lines—more served than the least frequented routes, yet less so than the most popular ones. Thus, the strategy adopted by the public transport company suggests that they are seeking a significant yet manageable benchmark to inform future service implementations. However, they appear to be cautiously avoiding the application of this new approach to their most frequently used routes in Pavia, likely to prevent major disruptions that could derive from unforeseen complications during the implementation and operation of the service.

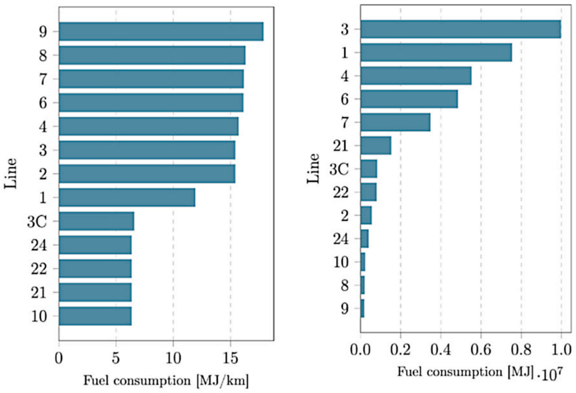
5.1. Energy consumption

This section focuses on analysing the energy consumption of the Pavia urban service, and it is divided into two scenarios: the diesel scenario and the electric scenario. The goal is to assess and compare the energy consumption in each of these scenarios for the urban transportation service.

In the diesel scenario, the analysis involves calculating both the kilometric fuel consumption and the absolute fuel consumption. Kilometric fuel consumption refers to the amount of fuel consumed per kilomiter travelled by diesel vehicles. This value is essential as it provides insights into the efficiency of fuel usage for each kilomiter covered during the service. On the other hand, the absolute fuel consumption represents the total amount of fuel consumed by diesel vehicles throughout the service period, without considering the distance covered. This value gives an overall measure of the total fuel consumption required to operate the urban service with diesel vehicles. In the electric scenario, similar calculations are performed, but instead of fuel consumption, the focus is on energy consumption. The kilometric energy consumption and the absolute energy consumption are calculated. The absolute energy consumption, like its diesel counterpart, represents the total amount of energy consumed by the EVs throughout the service period, regardless of the distance covered. This metric provides an overall measure of the total electricity consumption needed to operate the urban service with electric vehicles. Overall, this analysis allows decision-makers and stakeholders to make informed choices regarding the adoption of electric or diesel vehicles for the urban transportation service, considering factors like energy efficiency, environmental impact, and long-term sustainability.

5.1.1. Diesel scenario

As it was expected, it can be seen between Fig. 5a and b how there is a strict correlation between the kilometres offered by LPT



(a) Kilometric fuel consumption.

(b) Absolute fuel consumption.

Fig. 5. Energy consumption (diesel scenario).

company on Pavia's urban lines and the energy used to carry out the service: the most served lines are the ones that consume more fuel and the less served lines are the ones that consume less fuel. When looking at the kilometric fuel consumption in Fig. 6a, it has divided them into three different ranges.

- Between 6 and 7 MJ/km: on line 10, line 21, line 22, line 24 and line 3C; it is the lowest kilometric consumption of the three ranges, and it is since on these lines only the 7-m buses are used which are the smallest and lightest buses of the fleet.
- About 12 MJ/km: only on line 1; it is the middle value of kilometric fuel consumption and corresponds to a mixed used on the line of 7 and 12-m buses.
- Between 15 and 18 MJ/km: on line 2, line 3, line 4, line 6, line 7, line 8 and line 9; these are the lines that are served by only the 12-m buses, which are the biggest and heaviest vehicles in the urban area of the city of Pavia.

5.1.2. *Electric scenario*

As for the electric scenario, the two values presented in Table 2 are the result of a test conducted in the city of Pavia. Both types of electric buses were operated for a minimum of 9 h during the summer, with the air conditioning running at maximum power, albeit without any passengers onboard. The heating and air conditioning (HVAC) systems implemented in the setups considered are powered exclusively by electricity. It is possible to deduce that HVAC plays a fundamental role within the electric vehicle, significantly influencing the overall energy consumption. However, approximately 32 % was added to the tested consumption values to simulate a worst-case scenario, such as bus operation during peak hours and in temperature limit conditions (winter and summer). Table 2 also illustrates the amount of electrical energy in MJ required to service Lines 3C and 6. As anticipated, Line 6 consumes more energy than Line 3C since it employs 12-m buses as opposed to the 9-m buses used for Line 3C, and it covers hundreds of additional kilometres.

5.2. *The emissions*

This section will discuss the results from the analysis of the actual emissions made by the Pavia's urban service. The section analyses the two typologies of emissions: global and local. The first one focus on the CO_2 that is not harmful locally but increase the GHG effect. The second one focus on the combustion main pollutant products such as PM, NO_X and CO.

5.2.1. *Global emissions*

As mentioned in Section I, carbon dioxide is the primary contributor to the greenhouse effect and, consequently, global warming. However, it is not the only GHG that should be taken into account. This is why we often use the equivalent amount of carbon dioxide as a unit of measure for various GHGs.

Fig. 6 illustrates the equivalent carbon dioxide emissions per kilometre for each line, separated into two components: the WTT emissions, which account for the emissions produced during the production, transportation, and distribution of diesel, and the TTW emissions, which result from diesel combustion. This visual representation provides a clear overview of the environmental impact each line has in terms of carbon dioxide emissions, thereby facilitating a more informed assessment of the emission reduction strategies' effectiveness.

Regarding the Diesel scenario, the results indicate that the grams of CO_2 equivalent per kilometre (gCO_2eq/km) are consistent among lines served by the same type of bus. As anticipated, though, the emission values and minor variations among lines using the same bus type can be traced back to the differences in kilometric energy consumption depicted in Fig. 4. Consequently, Line 4 emerges as the most carbon-intensive in terms of kilometric global emissions. This understanding highlights the urgent need for mitigation measures, such as transitioning to cleaner energy sources, to reduce the environmental footprint of these bus lines. Fig. 6 vividly

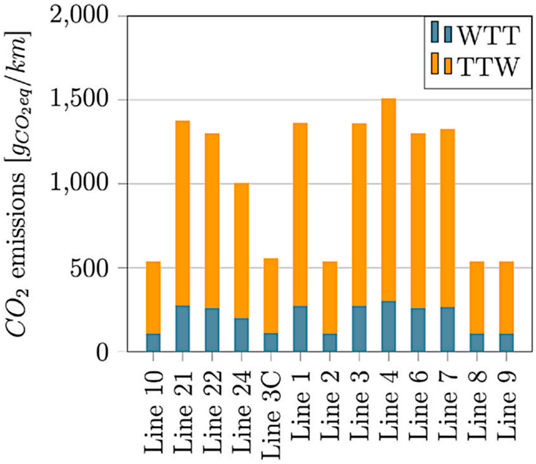


Fig. 6. Well to Wheel Emissions by line (Diesel case).

Table 2
Energy consumption for electric case.

Type of bus	Kilometric Consumption [MJ/km]	Absolute Consumption [MJ]
9-m	5.4	638′761.54
12-m	5.04	1′699′693.85

illustrates the significant contribution of TTW phase emissions (shown in orange) to the total emissions from the diesel fuel chain. Specifically, TTW emissions account for approximately 79.88 % of the total kilometric global emissions from Pavia's bus service. This finding underscores the critical role of on-road vehicle operations in shaping the overall environmental footprint of public transportation. It also emphasizes the importance of incorporating strategies like improving engine efficiency or adopting cleaner fuels to significantly reduce these TTW emissions, which could greatly impact the overall environmental sustainability of the public transportation service in Pavia.

Fig. 7 presents a comparative visualization of the projected CO_{2eq} emissions per kilometre under the electric scenario, juxtaposed with those of the diesel scenario. Upon complete transition to Battery Electric Vehicles (BEVs), Line 6 is expected to significantly curtail its CO_{2eq} kilometric production by a robust 68 %, reducing its emissions to 413 gCO_{2eq}/km. Similarly, Line 3C is projected to cut its emissions by 25 %, reaching 385 gCO_{2eq}/km. Therefore, substantial decrease in emissions emphasizes the environmental advantages of transitioning to electric buses. Beyond the immediate gains in terms of reduced CO_{2eq} emissions, this shift also has the potential to positively impact public health by reducing air pollution levels. Moreover, it aligns with global efforts to mitigate climate change, further highlighting the strategic importance of this transition in our move toward a more sustainable future.

As shown in Fig. 7, global emissions arising from the production, transmission, and distribution of electricity outweigh the diesel WTT phase emissions for both Line 6 and 3C by 36.5 % and 27.5 %, respectively. Despite this, the critical advantage of the electric power chain lies in its zero emissions from the TTW phase, which stands in clear difference from the diesel fuel chain, where the TTW phase contributes most GHG emissions. Results for the electric scenario are highly contingent on the specific energy mix utilized. Thus, with upcoming regulatory changes, the energy mix used for electricity production in European countries is expected to incorporate more renewable energy sources. This shift towards cleaner energy production is anticipated to substantially reduce the total CO_{2eq} emissions, further emphasizing the long-term environmental benefits of transitioning towards electric buses in public transport systems.

5.2.2. Local emissions

The local pollutants were calculated for each line under analysis, measured in g/km, Table 3. Subsequently, each result was compared with the legislation on emissions [47], which imposes not to exceed the following limits for diesel vehicles: Particulate Matter (*PM*) 0.005 g/km, *CO* emissions are 0.5 g/km, NO_x emissions are 0.080 g/km.

Values that exceed the limits set by the emission legislation are highlighted in orange and red. This event occurs only for some lines in the recorded values of NO_x, contrary to the other emission values which are within the limits. This comparison provides the environmental impact of these pollutants, particularly in urban locales where bus transportation is common. Further, it highlights the potential enhancements that transitioning to electric buses could bring about, especially in mitigating local pollutant emissions. Considering global emissions, the most significant benefit of the electric scenario lies in eliminating local pollutants due to the absence of combustion in BEVs. As an added note, this profound decrease in emissions contributes not only to a healthier environment, but also to improved air quality in urban areas, which can have profound implications for public health.

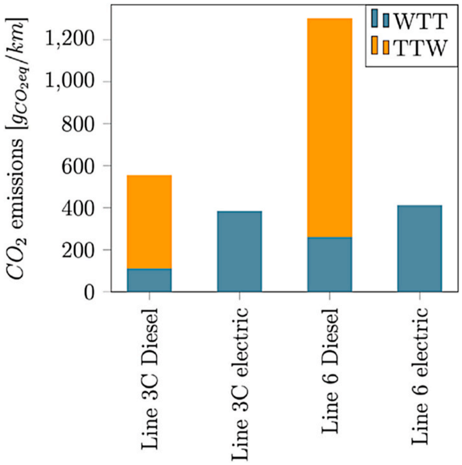


Fig. 7. Well to Wheel Emissions by line (Electric case).

Table 3
PM, CO and NOx emissions per km.

Line	*PM* [g/km]	*CO* [g/km]	NO_x [g/km]
1	0.0017	0.1897	0.5079
2	0.0003	0.0361	0.0967
3C	0.0005	0.0515	0.1380
4	0.0023	0.2514	0.6731
5	0.0014	0.1576	0.4218
6	0.0011	0.1280	0.3426
7	0.0008	0.0903	0.2417
8	0.0001	0.0134	0.0359
9	0.0001	0.0123	0.0330
10	0.0001	0.0154	0.0411
21	0.0001	0.0383	0.1026
22	0.0002	0.0383	0.1026
24	0.0001	0.0138	0.0368

5.3. Service

This section examines and discusses passenger counter data to depict daily bus occupancy patterns and estimate the number of buses needed for new services, focusing on two lines served by 7-m (21 seats) and 12-m (110 seats) buses. One of the aspects to highlight is the change in bus capacity resulting from the switch to electric buses. Electric buses, especially those the same length as their diesel counterparts, tend to have fewer seats due to the space taken up by battery packs and electric drivetrains. This reduction in seating capacity could potentially lead to difficulties accommodating the same number of passengers as before, which could raise service capacity issues [48].

5.3.1. Line served with 7 m buses: average passengers on board

The upward path, as shown in Fig. 8, does not exhibit any overcrowding situations, and the results are straightforward or trivial. This suggests that the occupancy levels along the upward path are well within the capacity of the transportation system, and there are no instances where the demand exceeds the available space on the vehicles. The absence of overcrowding situations indicates that the transportation service during the upward path is operating efficiently and can comfortably accommodate the passengers' demand without any issues.

As observable by Fig. 8 and Appendix A table 4, the time slot from the SOS to 9 a.m. has a maximum occupancy at 42 %, with only one run peaking at 71 % which can be considered an outlier regarding the time slot occupancy distribution. The 9–12 a.m. time slot has a less distributed situation, with 50 % of the runs between 19 % and 28 % level of occupancy, with a maximum of 33 % and a minimum of 14 %. The midday time slot sees a ride, with a peak of 38 % of occupancy due to the end of schools and thus the returning home of students. The 15–17 a.m. time slot also presents an analogous situation as the midday one with the absence of out-of-range runs and the distinction between first and second quartiles having 19 % and 21 % as occupancy values, respectively. The penultimate slot and the last slot consist of an undercrowded ride.

In general, the situation on the downward path, presented in Fig. 9, is much less crowded than on the ascending path. This means that the occupancy levels during the downward journey are lower, indicating that there is more available space on the vehicles and fewer passengers traveling in this direction compared to the ascending direction.

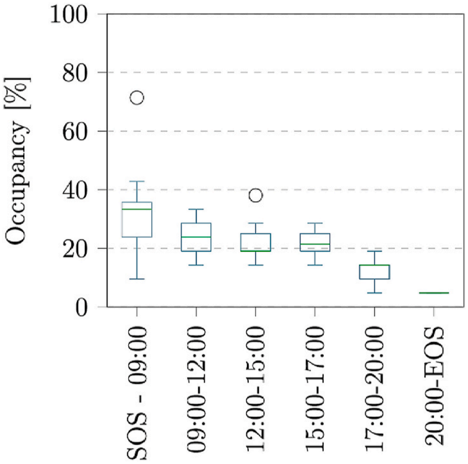


Fig. 8. The box plot of upward path based on average passenger.

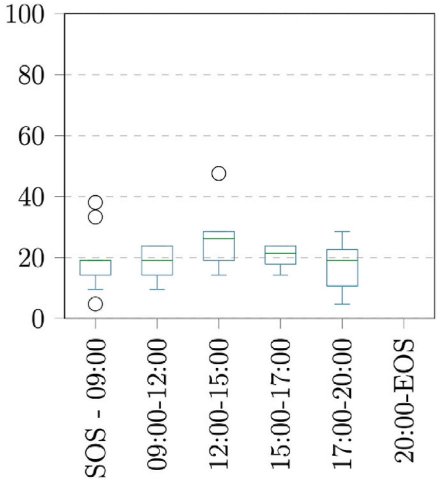


Fig. 9. The box plot of downward path based on average passenger.

In fact, as shown in Appendix A tables 5 and in the first time slot (SOS to 9 a.m.), 50 % of the rides have a level of occupancy between 14 % and 19 %, with some rides considered as outliers with their level approaching to 40 % and 50 %. What is interesting about the descending path is the initial complementary trend to the ascending one. In fact, as noted just before, the first time slot has a lower occupancy that then increases with a peak in the 12th-15th hours, and it decreases again as the day ends. This trend could be due to students and workers taking the line in the morning at the same hours, students returning home as soon as school ends in the early hours of the afternoon and workers distributing their returning home in the evening.

5.3.2. *Line served with 7 m buses: average passengers climbed*

Analysing the upward path shown in Fig. 10, the urban character of the service is emphasized by the average count of boarding passengers. Even though the buses do not seem overcrowded when looking at the average passengers onboard, the situation changes when considering the number of passengers boarding. The rides appear more congested, but not to a critical extent. Consequently, urban areas where frequent passenger turnover—"getting on and off"—is common. Furthermore, such findings could play a significant role in optimizing bus schedules and managing passenger flows for enhanced service efficiency and reduction of energy usage.

According to this consideration and regarding the upward path (Appendix A table 6), the outlier rides present in the SOS-9 a.m. time slot an occupancy level of 76 %, and 50 % of the rides of the same slot are comprised between the 28 % and 42 % of occupancy level.

The downward path, as depicted in Fig. 11 and described in Appendix A table 7, shows a similar situation to what was observed previously. The occupancy levels during the downward journey have slightly increased compared to the ascending path, but the overall trend remains less crowded.

In addition, since the 7-m buses are going to be replaced by 9-m buses that have greater capacity, this transition is potentially reducing the number of buses needed (if the company decides to reduce the frequency by putting together close rides) while reducing

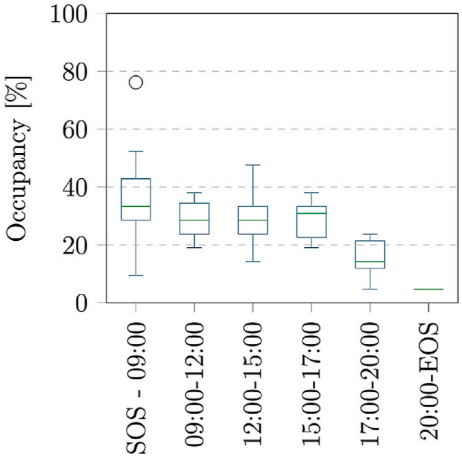


Fig. 10. The box plot of upward path based on climbed passenger.

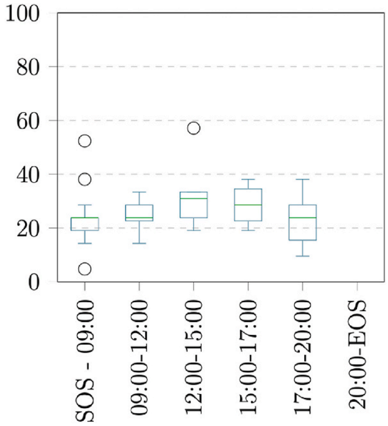


Fig. 11. The box plot of downward path based on climbed passenger.

at the same time the operating (as it is going to be shown in the profitability analysis) and staff costs.

5.3.3. *Line served with 12 m buses: average passengers on board*

Considering the upward path, as shown in Fig. 12, the first time slot has a minimum value of 3 % and a maximum value of 39 % of the level of occupancy and the 50 % of the rides are comprised between the 6 % and 20 %. The end of the peak-hour period is visible due to the reduction of the range in the second time slot, which has a maximum of 19 % of occupancy and a minimum of 7 %. The end of the school day is visible in the third time slot that has a maximum of 26 % occupancy and a minimum of 6 %. After this time slot, the occupancy starts to decrease, which reaches a maximum value of 10 % in the 20-EOS slot (Appendix A table 8).

In the 12-m situation, the complementary effect noted in the lines served by 7-m buses also repeats in this scenario. Indeed, the descendant path (Fig. 13 and Appendix A table 9) has a lower occupancy in the first time slot, with a maximum of 20 % of occupancy and only a ride with 35 % of occupancy. Then in the second time slot, the occupancy decreases with 17 % of occupancy and re-increases in the third slot (when the schools end) with 37 % and 32 % of occupancy. In this scenario, the outliers also appear during peak hours, in the first and third time slot.

5.3.4. *Line served with 12 m buses: average passengers climbed*

The urban nature of the transportation system is further confirmed by the occupancy values observed in the lines served by 12-m buses. In both the ascending and descending paths, as shown in Fig. 14a–b, respectively, there is an increase in occupancy levels compared to what was observed before for other types of buses. The rise in occupancy on these lines indicates that the demand for transportation is higher in urban areas served by 12-m buses. This could be due to several factors associated with urban settings, such as, higher population density or reduced private car usage in urban areas.

In the upward path, there are no outliers out of scale; their values are like the maximum and minimum values of the respective time band (Appendix A table 10). On average, the distribution is constant over the course of the day and 50 % of the trips are between 20 % and 30 %. Exceptions are the first band, SOS-9, in which a spike of 70 % is obtained, and the last band, 20-EOS, in which the level of employment drops to around 10 %. Compared to the upward path (Appendix A table 11), the outliers occur in the SOS-9 and

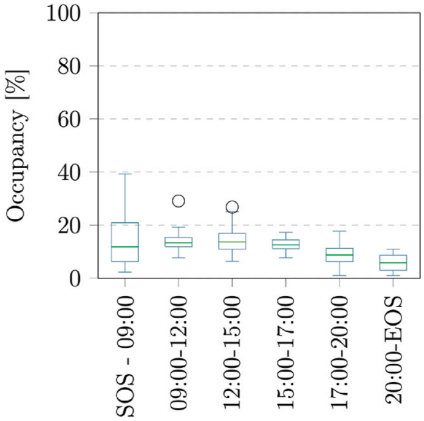


Fig. 12. The box plot of upward path based on average passenger.

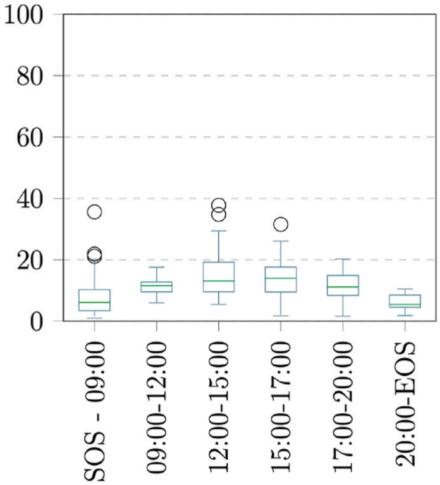
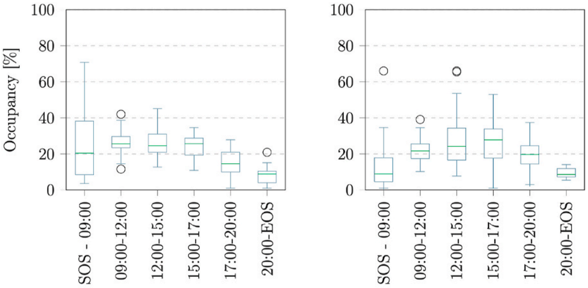


Fig. 13. The box plot of downward path based on average passenger.



(a) Upward path based on climbed.

(b) Downward path based on climbed.

Fig. 14. The box plots based on average passengers climbed.

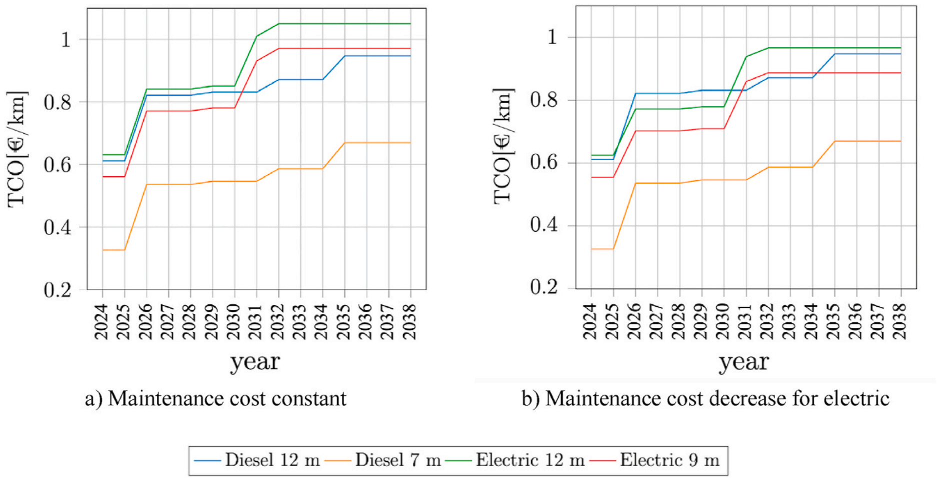
12:00–15:00 time slots, reaching maximum peaks of 66 %. In the first time slot, 50 % of trips are between 4 % and 17 % of the occupancy level. The following two time slots display substantial rises in their percentages, with the second slot fluctuating between 17 % and 25 % and the third slot varying between 16 % and 34 %. As the evening progresses into the final three time slots, a steep decline is observed, culminating in a maximum value of 14 % at the end of the shift.

5.4. *Profitability analysis*

The profitability analysis described in the manuscript considers both the time and the distance travelled (km/year), which means that the analysis evaluates the profitability of the investment over the lifespan of the buses (time) as well as the profitability based on the number of kilometres travelled per year. The first analysis regards the TCO (Tn) being calculated over 15 years on two scenarios: The same full-service maintenance cost coefficients for both the type of buses and a decrease of the maintenance costs for the electric one. Fig. 15a visualizes the first analysis considering that the buses cover an average distance of 55,000, 40,000 and 50,000 km, respectively, for the diesel and electric bus 12-m, the diesel 7-m and the electric 9-m. The growth of the TCO during the 15 years is due to the increase of the full-service maintenance coefficients as governed by the agreements with the supplier. The difference between the ICE buses TCOs and the BEV ones is due to the higher Capital Expenditures (CapEx) needed to implement an electric service, and thus it is necessary to buy the bus, substitute the battery, train and acquire staff and for the infrastructure.

In the second scenario, depicted in Fig. 15b–a 30 % reduction in operational costs (excluding energy costs) is assumed for all 15 years. Despite this, BEV buses are still more expensive than ICE buses, except from the third to the seventh year, when the 12-m BEV bus becomes more economically viable. However, the costs escalate again with the replacement of the battery. The 9-m bus continues to be pricier than the 7-m variant due to its higher traction cost, making the latter the most affordable among all four types.

The other analysis focused on varying the average distance covered by the buses in a year to determine the minimum number of kilometres required for electric buses to become less expensive than diesel buses, assuming the diesel buses maintain their average yearly distance as considered before. The results are divided into three macro-scenarios, each presenting different conditions for comparison, where the term “contributions” refers to funding provided by the public entity. Therefore, when stating “No contributions,” it means that both electric buses and diesel-powered buses are entirely the responsibility of the operator.



a) Maintenance cost constant

b) Maintenance cost decrease for electric

Fig. 15. TCO in 15 years, from 2024 to 2038.

In the first macro-scenario, “Both contributions” (Fig. 16a–b), where both electric and diesel buses have the same maintenance costs, the electric buses never prove to be more cost-effective than their diesel counterparts, even if the distance covered is doubled. Additionally, even with a reduction in Operational Expenditure (OpEx), electric buses still end up being more expensive than diesel buses, except for the 9-m electric bus, which closely follows the cost trend of the 12-m diesel bus without significant differences.

In the second macro-scenario, “No Diesel contribution” (Fig. 16c–d), with no additional contributions from diesel buses, both the 9-m and 12-m electric buses consistently prove to be cheaper than the 12-m diesel bus, even with a lower distance covered. Moreover, even with reduced maintenance costs, electric buses remain more cost-effective than the 12-m diesel-powered bus. In particular, the 9-m electric bus outperforms the 7-m diesel bus in cost-effectiveness if the distance covered is at least 65,000 km per year.

The third macro-scenario, “No contributions” (Fig. 16e–f), assumes no additional contributions for either type of bus. Diesel buses are consistently more cost-effective, assuming the same maintenance costs. However, if maintenance costs are reduced, electric buses become more competitive with diesel buses. Specifically, to achieve the same level of TCO for the 12-m buses, the electric buses need to cover a distance of at least 100,000 km per year. On the other hand, the 9-m electric bus becomes more cost-effective than the 12-m diesel bus starting from 55,000 km in a year.

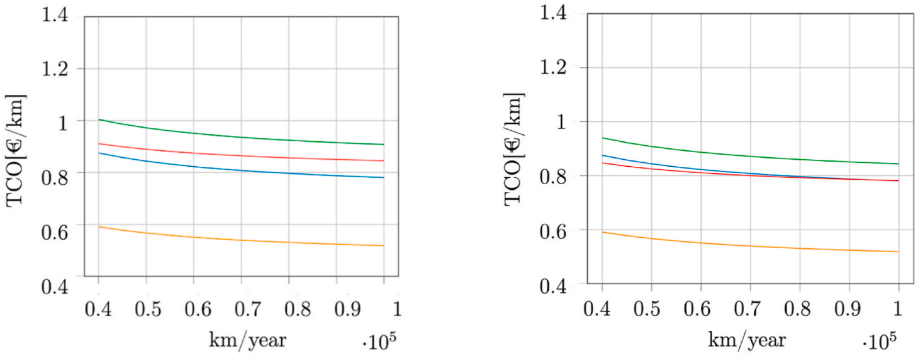
In summary, the study consistently supports the economic viability of the “No Diesel contribution” scenario, especially with 9-m and 12-m electric buses, showcasing their profitability over the 12-m diesel bus across varying travel distances. Notably, the cost-effectiveness of electric buses remains superior even when considering reduced maintenance expenses. These findings underscore the significant economic advantages associated with investing in electric buses, particularly those with a 9-m length. This recommendation aligns seamlessly with the broader objective of transitioning towards a more sustainable and environmentally friendly public transportation system. Policymakers and investors are urged to give due consideration to this scenario, recognizing not only the economic benefits but also the positive contribution to greener and more sustainable practices within the public transportation sector.

The study highlights the pivotal role electric buses can play in ongoing efforts to mitigate environmental impact, lower greenhouse gas emissions, and promote a sustainable future for urban mobility. As advancements in electric vehicle technology progress and associated costs decrease, the economic feasibility of electric buses is expected to further enhance, solidifying their position as a crucial element in the evolution towards a cleaner, more efficient public transportation infrastructure [50,51]. The integration of electric buses stands as a key step in fostering a transformative shift towards sustainable urban transportation.

6. Conclusions

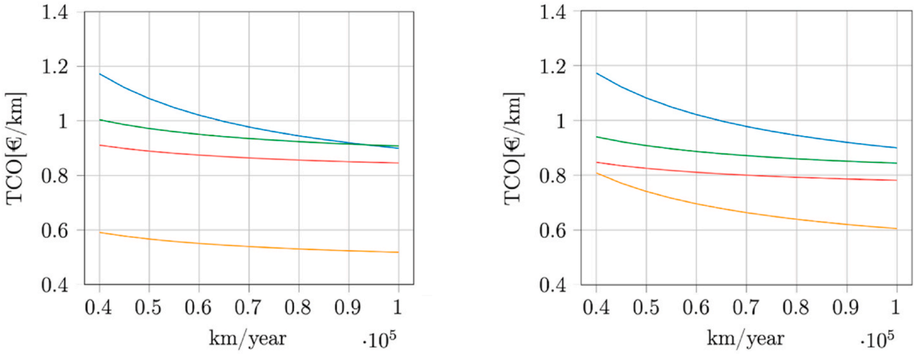
This study shows a comparison analysis between two different configurations of public transport vehicles, diesel, and electric, considering various aspects. First, the current production of GHG is estimated by comparing it between the two types of buses. Subsequently, an estimation of the consequences of the fleet renewal on the service was carried out, assessing the impacts of the change in bus capacity resulting from the switch to alternative technology. Finally, a profitability analysis is made that estimates the TCO as a function of bus helpful life and as a function of the average kilometres per year.

The results showed that the goal pursued by the EU Institution is partially achieved by switching to BEV because overall emissions are significantly reduced. The results show that through electric technology, a 68 % reduction in global emissions is expected when comparing diesel buses with the same length and considering a WTW approach. This is mainly because the energy mix to produce electricity is about 50 % renewables and 50 % fossil fuels, leaving ample room for further reduction in global emissions. So, the investment must also be on power generation, focusing on low- and zero-emission generation sources. When considering local pollutants, EVs offer a significant advantage as they do not produce such emissions, making them a more environmentally friendly option compared to diesel buses. The study revealed that the recorded NO_x levels occasionally surpassed the legal limits, contrary to other



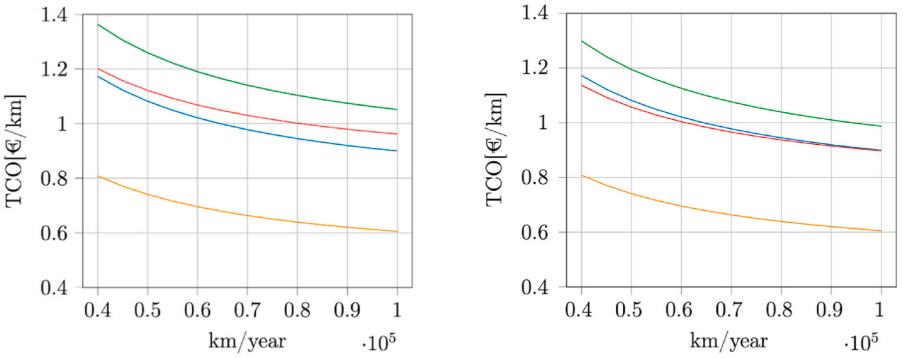
(a) Same maintenance costs with both contributions.

(b) Maintenance costs reduction with both contributions.



(c) Same maintenance costs without diesel contribution.

(d) Maintenance costs reduction without diesel contribution.



(e) Same maintenance costs without contributions.

(f) Maintenance costs reduction without contributions.

Fig. 16. TCO analysis based on km/year.

emissions, which remained within acceptable boundaries. This finding highlights that NO_x emissions remain a notable issue associated with some diesel vehicles.

While EVs are and will be more environmentally sustainable than diesel-powered vehicles, it is not evident from a social and economic perspective. In terms of service, the change of timetable and fewer seats of BEVs (if of equal length) may lead to negative impacts from a social sustainability perspective. For now, the diesel scenario is always more profitable for the same bus length and distance travelled. However, in the coming years, it is expected that the CapEx to be spent on implementing an electric bus service will be lower because the cost of buses, batteries, charging infrastructure, and component replacements will be reduced. Furthermore, considering the cessation of government incentives on diesel in the future, combined with the increased efficiency derived from the acquired know-how and implementation of Bus to Grid systems, as well as the resale of batteries, it is anticipated that the TCO of the electric scenario will decrease, thereby becoming lower than that of the diesel scenario.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Seyed Mahdi Miraftabzadeh: Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Saldarini:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Cattaneo:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastiano El Ajami:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michela Longo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Federica Foiadelli:** Writing – review & editing, Validation, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table 4
Percentage boxplot average passenger on board ascendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	11	12	12	8	11	1
min	9 %	14 %	14 %	14 %	4 %	4.7 %
Q1	23 %	19 %	19 %	19 %	19 %	
Q2	33 %	24 %	19 %	21 %	14 %	
Q3	35 %	28 %	25 %	25 %	16 %	
max	42 %	33 %	38 %	28 %	19 %	

Table 5
Percentage boxplot: average passenger on board descendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	13	12	12	8	10	NA
min	5 %	9 %	14 %	14 %	4 %	
Q1	14 %	14 %	19 %	17 %	10 %	
Q2	19 %	19 %	26 %	21 %	19 %	
Q3	19 %	23 %	29 %	23 %	22 %	
max	38 %	26 %	47 %	23 %	28 %	

Table 6
Percentage boxplot: average passenger climbed ascendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	11	12	12 %	8	11	1
min	9 %	19 %	14 %	19 %	5 %	5 %
Q1	28 %	23 %	23 %	22 %	12 %	
Q2	33 %	28 %	29 %	31 %	14 %	

(*continued on next page*)

Table 6 (*continued*)

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Q3	42 %	35 %	33 %	33 %	22 %	
max	76 %	38 %	47 %	38 %	24 %	

Table 7
Percentage boxplot: average passenger on board descendant

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	13	12	12	8	10	NA
min	5 %	14 %	19 %	19 %	10 %	
Q1	19 %	22 %	24 %	23 %	15 %	
Q2	24 %	24 %	30 %	29 %	24 %	
Q3	24 %	29 %	33 %	35 %	29 %	
max	52 %	33 %	47 %	38 %	38 %	

Table 8
Percentage boxplot: average passenger on board ascendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	51	44	45	35	76	19
min	3 %	7 %	6 %	3 %	2 %	2 %
Q1	6 %	11 %	11 %	11 %	6 %	3 %
Q2	11 %	13 %	14 %	12 %	8 %	6 %
Q3	20 %	15 %	17 %	14 %	11 %	8 %
max	39 %	19 %	26 %	17 %	17 %	10 %

Table 9
Percentage boxplot: average passenger climbed descendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	62	44	42	37	76	5
min	2 %	6 %	5 %	3 %	2 %	2 %
Q1	7 %	10 %	9 %	9 %	8 %	4 %
Q2	6 %	12 %	13 %	14 %	11 %	5 %
Q3	10 %	13 %	19 %	17 %	15 %	8 %
max	20 %	17 %	37 %	32 %	20 %	10 %

Table 10
Percentage boxplot: average passenger climbed ascendant.

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	51	44	45	35	76	19
min	3 %	11 %	12 %	2 %	3 %	2 %
Q1	8 %	23 %	21 %	19 %	10 %	4 %
Q2	20 %	25 %	24 %	25 %	14 %	8 %
Q3	38 %	29 %	31 %	28 %	21 %	10 %
max	70 %	42 %	45 %	34 %	28 %	21 %

Table 11
Percentage boxplot: average passenger climbed descendant

	SOS-9:00	9–12	12–15	15–17	17–20	20-EOS
Number of rides detected	62	44	42	38	76	5
min	3 %	10 %	7 %	2 %	3 %	5 %
Q1	4 %	17 %	16 %	17 %	14 %	7 %
Q2	8 %	19 %	27 %	24 %	21 %	9 %
Q3	17 %	25 %	34 %	33 %	24 %	11 %
max	66 %	39 %	66 %	52 %	37 %	14 %

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