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Mitigating urban pollution: A comparative life cycle assessment of hydrogen, electric, and diesel buses for urban transportation

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ABSTRACT

Urban transportation systems, particularly public buses, contribute significantly to global pollution, creating an urgent need for sustainable solutions. Alternative fuel buses and other disruptive technological advancements in this field are essential to resolve these problems. The absence of studies on the life cycle assessment (LCA) of hydrogen-fueled buses, along with comparative analyses of alternative-fueled buses, makes this research particularly timely. This study develops a comprehensive LCA framework to measure the economic and environmental impact of using different technologies (i.e., hydrogen-fueled, electric, and diesel buses). Different fuel production methods were examined, considering operational factors such as energy consumption across various routes. This study contributes to enhancing the LCA methodology for public bus operations by using machine learning algorithms to cluster routes and identify optimal demonstration routes for analysis. The results highlight the impact of fuel production methods for hydrogen-fueled buses in the significant pollutant reductions (e.g., CO_2 and NO_x), despite their high life cycle costs. The proposed framework is validated with real data from Halifax, Canada, and expanded to assess public bus networks in cities with varying routes, topology, and population levels. The paper's analyses consider future technological advances to lower costs, aligning them with electric buses over time. This study helps policymakers choose the best public bus alternatives to improve the economic, environmental, and social sustainability of urban transportation.

1. Introduction

Urban transportation is essential for a prosperous and socially active society, enabling mobility, social interaction, economic growth, and improving quality of life; however, it also poses significant environmental challenges, particularly in terms of pollution and sustainability [1]. The widespread use of fossil fuels in vehicles has an adverse effect on public health and speeds up climate change through greenhouse gas (GHG) emissions and global warming [2]. According to statistics, fossil fuels provide more than 80% of the energy used worldwide [3,4]. Approximately 20% of the primary energy demand in the world, 28% of its final energy consumption, and 23% of global emissions are attributed to the transport sector, which also contributes around 14% to global GHG emissions, including other gases such as methane [5,6]. Across the globe, there are 1.2 billion passenger cars and 380 million commercial vehicles. Currently, about 95% of transportation energy comes from petroleum-based fuels, consuming approximately 60% of global oil production [5]. Globally, efforts to reduce pollution are increasing. Under the Paris Agreement, for example, participating countries aim to limit global warming to approximately 1.5 degrees Celsius [7].

Given that the transportation sector is one of the major consumer of energy [8], it is crucial to explore the impact of various fuel types on decarbonizing transportation. Previous research indicates that achieving this goal is particularly challenging in the transportation sector compared to others. To further address sustainability challenges of the transportation sector, an environmentally sustainable policy is needed that ensures that the transportation sector maintains its functionality while minimizing its adverse environmental impacts [9,10].

A comprehensive policy for transitioning to a sustainable public transportation requires stakeholders' involvement. Among different stakeholders, governments play an essential role in setting policies and regulations. Mass adoption of sustainable transportation solutions is accelerated by strong policy frameworks and effective governance, underscoring the importance of governmental support and action. Governments also advocate for public interests, social values, and environmental targets. This entails making investments in public transportation

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Table 1
Abbreviations and acronyms.

Abbreviation	Description
GHG	Greenhouse Gas
CO_2	Carbon dioxide
PM10	Particulate Matter 10 μm or less in diameter
PM2.5	Particulate Matter 2.5 μm or less in diameter
NO_x	Nitrogen Oxides
VOCs	Volatile Organic Compounds
SO_x	Sulfur Oxides
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
SI	Sustainability Index
CNG	Compressed Natural Gas
LNG	Liquefied Natural Gas
FCEVs	Fuel Cell Electric Vehicles
BEVs	Battery Electric Vehicles
WTW	Well-to-Wheels
EU	European Union
FC	Fuel Cycle
EV	Electric Vehicle
VC	Vehicle Cycle
PEM	Polymer electrolyte membrane
ICEs	Internal combustion engines
LCIA	Life Cycle Impact Assessment
LCI	Life cycle inventory
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HRM	Halifax Regional Municipality
HTGR	Hydro and solar energy, high-temperature gas-cooled reactors
RE-NG	Renewable natural gas
TCO	Total cost of ownership
FCVs	Fuel Cell Vehicles
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
WCSS	Within-cluster sum of squares
VT-CPFM	Virginia Tech comprehensive power-based fuel consumption model
HDVs	Heavy-duty vehicles

Table 2
Comparison the characteristics of hydrogen, diesel, and electric buses [23].

Feature	Hydrogen buses	Diesel buses	Electric buses
Cost	High initial cost, lower operating costs	Moderate initial cost, higher operating costs	High initial cost, lower operating costs
Refueling/Recharging Time	5–10 min	5–10 min	4–6 h (standard), 1–2 h (fast)
Risk	Moderate (flammability, pressurized storage)	High (flammability, pollution)	Low (battery risks, electrical hazards)
Battery Life	5–10 years	Not applicable	8–12 years
Travel Range	300–400 miles	300–500 miles	100–200 miles

networks [11], providing incentives for the use of hybrid and electric cars [12,13], and building infrastructure that facilitates the use of alternative forms of mobility such as walking and cycling [14]. In particular, governments can encourage the development of green technologies (e.g., modernizing public bus fleets using sustainable fuels) through research and development as well as setting stricter emissions requirements [15]. Such investments in sustainable mobility, improves public health, lessens reliance on fossil fuels, and builds economic resilience in addition to assisting in the mitigation of environmental effects [16]. Furthermore, collaboration with private sectors, non-for-profit organizations, financial institutions, and the public is crucial to effectively implement and promote sustainable practices [17]. Involvement of all stakeholders can guarantee a future that is cleaner, healthier, and more sustainable for citizens by giving priority to sustainable transportation programs.

In order to achieve a sustainable mobility and solve the environmental issues related to the transportation industry, focusing on the public transportation is essential. Public transportation systems, such as buses, trains, and subways, provide an effective and accessible alternative to driving private vehicles, drastically reducing the number of automobiles on the road and lowering the overall GHG emissions [18]. Infrastructure improvements for public transportation not only reduce traffic congestion but also advance social fairness by giving all residents, including those without private cars, access to affordable mobility options [19]. Governments worldwide are increasingly acknowledging the pivotal role of public transportation in mitigating urban carbon emissions, thereby offering initiatives to modernize and expand these transportation systems. To modernize urban transportation systems using sustainable fuels, several alternatives, as introduced in Table 2, are considered, each offering unique opportunities and challenges. While technology and infrastructure for more sustainable fuels are under development, bio-diesel and natural gas are seen as transitional fuels that can help reduce dependency on conventional diesel fuel. Additionally, electrification of public transportation, using battery-powered electric buses, provides an immediate reduction in greenhouse gas emissions and is effective in urban settings with pre-established charging infrastructure. Among these options, green hydrogen. Produced via electrolysis powered by renewable energy sources, green hydrogen emerges as a compelling solution [20] as it does not emit pollutants at the point of use, and thus, is considered as one of the cleanest fuels available [21]. Its high energy density compared to batteries also allows for longer driving ranges and shorter refueling times, addressing some of the major operational limitations of electric buses [22]. Also, green hydrogen can be integrated into existing energy systems, providing a versatile pathway to decarbonize public transportation while supporting the broader adoption of renewable energy technologies. This positions green hydrogen as a viable and strategic solution for cities committed to decarbonize their transportation systems.

Canada has become a key destination for immigrants in recent years. From 2015 to 2025, the nation's population increased by approximately 16% (Fig. D.1 in the supplementary material). The projections suggest that under a medium growth scenario, the population could reach 60 million and under a high growth scenario, it could rise to 75 million, indicating a substantial rise [24]. Halifax, Nova Scotia, has particularly emerged as one of the country's preferred cities to settle down. This growth has precipitated various transportation challenges. In response, the local government has been enhancing the quality of public transport by expanding the bus fleet. However, this solution could potentially increase pollution over the long term, posing a conflict with Halifax's goal of achieving net zero emissions by 2050. The geographical location of the city uniquely positions it to take advantage of renewable energy sources, such as hydrogen, particularly within its transportation system.

While numerous studies have studied the viability of using renewable energy sources in private cars, the literature lacks similar studies for public transportation systems, particularly buses. Due to the financial barriers to adopting alternative fuel private cars, the incorporation of renewable fuels into public transportation is crucial. In addition, limited attention has been paid to the varying environmental impacts of different fuel production methods in the context of bus transit systems. In addition, the literature lacks investigation of how operational conditions (for example, weather conditions, city topology) can potentially influence the environmental impact of public transportation systems. This consideration is absolutely important due to the connection between operational conditions and the fuel consumption of a transportation fleet. Although transportation technologies based on renewable energy sources have not yet fully matured, any relevant study should consider how the cost and environmental impacts of renewable energy sources will evolve in the future. This represents another gap in the literature, necessitating a more in-depth analysis grounded in credible academic sources.

To address the existing gaps in the literature, this study examines the viability of utilizing hydrogen-powered buses in urban transportation settings. The proposed study uses the LCA method, as a

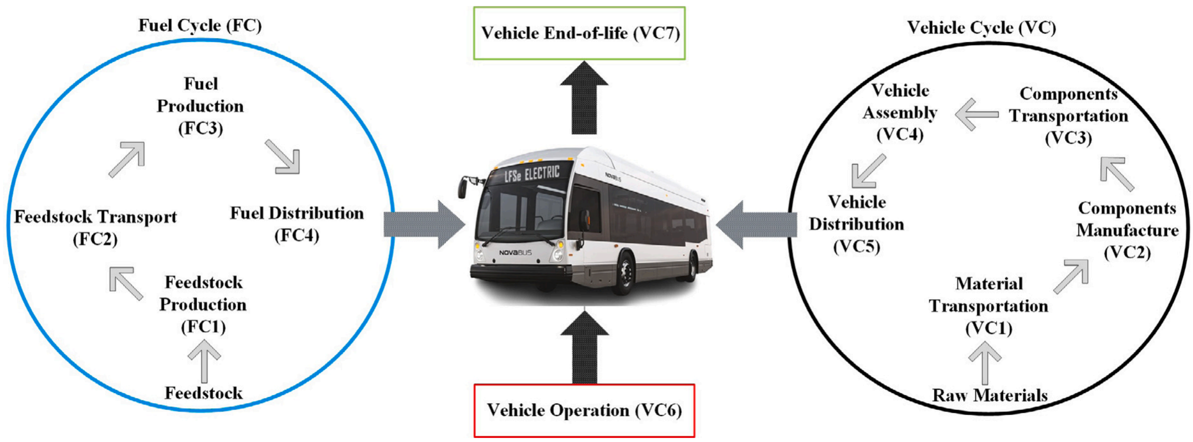


Fig. 1. The schematic view of the Life Cycle Inventory elements for public buses.

cradle-to-grave approach, to evaluate technologies used in public bus transportation systems in urban settings [25]. The developed assessment framework involves making an inventory of pertinent inputs and outputs, evaluating the possible environmental effects of all inputs and outputs that have been identified, and interpreting the findings [26]. LCA provides detailed information on the role that each stage of the life cycle will have on the total environmental impact of the product (for example, the emission of fuel production and consumption) [27]. As a result, the literature portrays LCA as a suitable method to determine the relative advantages of various options for urban mobility. The general fuel and different stages of the vehicle's life cycle are shown in Fig. 1. FC (blue section) represents the total emissions of the entire fuel life cycle. While stages FC1 to FC4 denote the emissions from the fuel production phase, VC6 represents the emissions produced during the fuel consumption phase (red).

The ultimate goal of this study is to investigate the environmental and economic impacts associated with alternative fuels (i.e., hydrogen, electric, and diesel) in public bus transportation based on a real case study. Thus, the objectives of the proposed research include performing a comprehensive LCA to compare environmental impacts, analyzing life cycle costs (LCC) to illustrate economic viability of alternative fuels, investigating different fuel production methods, clustering public transportation routes using machine learning tools, and forecasting the effects of technological advancements on different fuel adoption rates.

This study contributes to the literature on theory, practice, and policy development. First, it provides a detailed comparative analysis of the environmental impacts of different types of fuel, enriching the body of knowledge with detailed insights into how different types of fuel and their production methods, will impact sustainability of public transit systems. Second, it analyzes the economic feasibility of different fuel types during their life cycle, offering a critical perspective that assists stakeholders in making informed investment decisions. Furthermore, the application of machine learning techniques in route selection introduces a novel methodological approach that bridges the gap between theoretical research and practical applications. This study also delineates the policy implications of adopting alternative fuel types, serving as a tool for policymakers looking to reduce urban transportation emissions. Lastly, this research considers future technological developments, through which a forward-looking analysis is prompted that helps anticipate changes in the transportation sector, ensuring that today's decisions remain relevant in the evolving landscape of public transportation. In total, the contributions of this research not only fill significant gaps in the current literature but also provide stakeholders with quantitative tools to improve the sustainability and efficiency of urban transit systems.

The remainder of this paper is organized into five sections. Section 2 reviews the literature on LCA applications in various modes of transportation, including public transportation. Section 3 describes the problem under consideration and presents the proposed LCA framework for different types of buses. Section 4 presents numerical results, including a machine learning approach for clustering public bus routes. It analyzes real data and compares findings with relevant studies for deeper insights. Managerial insights are discussed in Section 5. Finally, Section 6 presents conclusions and future research directions.

2. Literature review

This section provides an overview of the literature pertaining to the environmental assessment methods used in the transportation systems. In particular, a comprehensive analysis of using LCA in the public transportation is first presented. Then, studies that use LCA in other transportation modes, such as private cars and trucks are discussed. At the end, this section summarizes research gaps that will be addressed in the proposed research.

2.1. Life cycle assessment in the public transportation

Environmental impacts of using different types of fuel in the public transportation has been studies in [28] where the use of diesel, biodiesel, compressed natural gas (CNG), liquefied natural gas (LNG), hybrid (diesel–electric), and battery electric (BE) have been analyzed for public transit buses. Through the LCA method, the authors found that the BE transit buses cause significantly lower CO_2 emissions than other alternative fuel types.The paper also demonstrated that certain operating patterns of hybrid-powered transit buses generate emissions levels comparable to those of BE transit buses. The environmental impacts of replacing diesel buses with CNG buses in urban transportation in Poland demonstrated that over the operational life cycle of a CNG bus, there is a reduction of 400 kg in GHG emissions and 52.5 kg in particulate emissions compared to a diesel bus [29]. Another study compared the environmental impact of using conventional diesel and electric buses in the transportation system in the US using LCA [30]. The results of this study revealed that during the operational phase, electric-powered buses exhibit significantly better environmental performance than the diesel ones. However, accounting for the production of batteries, diesel buses exhibited better performance in some measures such as global warming and ozone depletion. The environmental impacts of public bus transportation systems fueled by diesel, hydrogen, and natural gas were studied through an LCA approach in Perth, Western Australia, and employed an LCA approach [31]. The findings illustrate that emissions contributing to the acidification and photochemical ozone formation are greater for fuel cell buses. An LCA study for public bus transportation system analyzed the impacts of electric engine buses powered by compressed hydrogen fuel cells of polymer electrolyte membrane (PEM) in Rosario, Argentina [32]. The study considered both renewable (green hydrogen), such as post-industrial wood residues, and non-renewable (gray hydrogen), such as local electrical power for the hydrogen production process. The findings indicated that a number of variables, including the energy content of the raw materials and the required electrical energy for the hydrogen production process have a significant impact on the environmental and energy viability of producing hydrogen for use in public buses. [33] applied LCA approach to analyze the environmental impacts of public transportation. They considered various scenarios and policies to assess emissions and define a sustainable profile for the current and future in their case study. The results illustrated that while transportation system management typically falls under municipal jurisdiction, the greater significance of environmental impact depends on national policies regarding the use of biodiesel in diesel fuel. Another study based on LCA method analyzed GHG emissions in the public transportation system of Curitiba, Brazil [34]. The study considered conventional, hybrid–electric, and plug-in hybrid–electric city buses, and real-time data was used to develop a simulation model. The results showed that hybrid–electric and plug-in hybrid–electric buses resulted in lower emissions than the other types of buses.

Based on the reviewed literature, it is evident that, with a predominant focus on electric, diesel, or gasoline alternatives, hydrogen is often overlooked in studies. Moreover, in studies where hydrogen is studied as an alternative fuel, only environmental impacts have been assessed. However, to fully evaluate the sustainability of adopting hydrogen in public transportation, it is essential to consider social and economic factors.

Lubecki et al. [35] conducted a comparative LCA of hydrogen, electric, and diesel buses, emphasizing that hydrogen and electricity can significantly reduce global warming potential if sourced from low-emission energy. Their findings highlight the importance of prioritizing renewable energy sources for hydrogen and electricity production to maximize environmental benefits. Similarly, Chang et al. [36] assessed the carbon footprint of alternative energy buses in Taiwan, revealing that hydrogen fuel cell buses had the lowest emissions compared to LNG, diesel, LPG, and electric alternatives. Their study suggests that replacing urban diesel buses with hydrogen buses could substantially cut CO_2 emissions. Likewise, Jelti et al. [37] assessed alternative fuels for city buses in Morocco and concluded that electric and fuel cell buses performed best in terms of sustainability. Their research underlined the potential benefits of deploying these alternatives to mitigate urban air pollution. While many studies point to the benefits of hydrogen buses, some also highlight their challenges. Agostinho et al. [38] analyzed the environmental performance of hydrogen buses in São Paulo, Brazil, and found that while hydrogen has a lower global warming potential than diesel, its production is still highly dependent on fossil energy. Their study reinforces the need for integrating renewable energy sources into hydrogen production to enhance sustainability. Further reinforcing these insights, Grazieschi et al. [39] compared the energy consumption and GHG emissions of electric and hydrogen buses in Bolzano, Italy. They observed that electric buses achieved a 43% reduction in primary energy demand and a 33% reduction in global warming potential compared to diesel. However, the study also noted that the environmental impact of hydrogen buses varied depending on the production method, with steam methane reforming leading to significantly higher emissions. Similarly, Pederzoli et al. [40] examined the life cycle emissions of hydrogen-powered buses in the High V.LO-City project and emphasized that while hydrogen buses can reduce emissions during operation, their overall sustainability depends on using clean electricity for hydrogen production. Their study calls for stronger policy interventions to ensure a low-carbon hydrogen supply and efficient energy infrastructure. Muñoz et al. [41] conducted a comparative analysis of the costs, emissions, and fuel consumption of diesel, natural gas, electric, and hydrogen urban buses in Argentina. Their findings indicate that while compressed natural gas buses currently offer a cost advantage, electric and hydrogen buses are projected to become cost-competitive by 2030. Notably, transitioning to hydrogen fuel cell buses could lead to an 87% reduction in GHG emissions, making them the most promising long-term solution for sustainable urban transport. In another interesting study, François et al. [42] utilized a mathematical life cycle model to calculate the total cost of ownership and the total environmental impact of hydrogen, diesel, and electric buses. They applied this model to Réunion Island as a case study. The results indicate that hydrogen vehicles are currently more expensive than battery-powered ones. If optimizing a fleet composed of various types of vehicles, it would be economically advantageous to have a greater number of electric vehicles (EVs) than hydrogen ones. Gazda-Grzywacz et al. [43] also employed the LCA approach to analyze hydrogen, electric, and diesel-powered buses. They simulated the model over a 15-year period, assuming a travel distance of 1,000,000 km. The results illustrated that hydrogen buses outperformed electric buses across all 11 environmental impact categories (e.g., global warming, ozone depletion) and exceeded conventional diesel buses in 5 of the 11 categories.

2.2. Life cycle assessment for non-public vehicles

LCA is also applied to vehicles other than the public transit buses. The environmental impacts of using hydrogen and electric vehicles were evaluated using LCA in Tuscany, Italy [44]. The study assumed renewable wind and biomass energy sources for hydrogen production, and the results indicated that using renewable energy sources, for hydrogen and electricity generation, results in superior environmental performance across most of the impact categories compared to the Italian national electricity mix. The environmental impacts of hydrogen fuel cells in passenger vehicles in four provinces in Canada (i.e., British Columbia, Alberta, Ontario, and Quebec) were studied in [45]. The study compared different hydrogen production methods with conventional gasoline in vehicles and the results showed that thermochemical hydrogen production yields the most favorable results in all provinces due to the prospective use of renewable waste heat. Furthermore, the use of renewable hydroelectric power for electrolysis in Quebec and British Columbia was found to be the second most favorable hydrogen production approach. A thorough LCA study of fuel cell, electric, and internal combustion engine vehicles in China was conducted in [46] where various hydrogen production scenarios and driving mileages of vehicles were taken into account. The findings revealed that throughout the vehicles' lives, electric vehicles have substantially higher primary energy consumption and GHG emissions than the other two and this can be attributed to high energy consumption and emissions associated with their battery manufacturing. In [47] the GHGenius database [48] was used to analyze the total amount of emissions released during the lifespan of light-duty commercial vehicles powered by CNG and diesel fuel using real-time data in Surrey, Canada. The results showed that GHG emissions could be reduced by 34% through replacing diesel vehicles with CNG vehicles. Moreover, [49] also examined the impacts of replacing conventional fossil-fueled vehicles with hydrogen and electric-powered vehicles in the US and evaluated energy consumption and GHG emissions using an LCA approach. For hydrogen production, the study considered technologies such as steam reforming of natural gas, electrolysis powered by wind energy, and coal gasification and found that replacing conventional fossil-fueled vehicles with hydrogen-powered ones significantly reduces emissions associated with air pollution. In the study conducted by [50], the focus was on the production processes of hydrogen and electricity for vehicles that use natural resources as their source. The objective was to compare the energy efficiency of vehicles powered by hydrogen and electricity with those powered by methane gas. This comparative analysis, carried out within the context of Sweden's transportation system, employed a LCA methodology. The results of the study revealed that hydrogen FCVs demonstrate an energy efficiency comparable to methane gas vehicles, even when the latter are powered by biomethane. Additionally, the study suggested that an increase in the consumption of hydrogen is likely to have a minor impact on Sweden's primary energy supply, contrary to earlier expectations. The benefits of integrating hydrogen energy into the transportation network were studied in [51] where the energy consumption and GHG emissions over the lifespan of vehicles were analyzed. The results indicated that for a hydrogen-powered vehicle to compete with a gasoline-powered one, its efficiency needs to be nearly 30% higher than for gasoline vehicles. The study also highlighted the importance of studying hydrogen production methods and their environmental impacts in the future. In a related study, [52] examined the environmental impacts of using specific renewable resources, such as wind and solar power, for hydrogen production in comparison to conventional hydrogen production using grid electricity in the UK. The findings indicate that, in light of the UK's energy policies projected through 2030, leveraging a strategic mix of these renewable production methods could be the most advantageous approach for hydrogen generation. A comparative analysis of three distinct pathways utilizing natural gas as an energy source for vehicles was explored in the study by [53]. These pathways include: (1) using compressed natural gas (CNG) directly as fuel in combustion engines, (2) reforming natural gas to produce hydrogen for fuel cell electric vehicles (FCEVs), and (3) generating electricity from natural gas to power battery electric vehicles (BEVs). The study focused on analyzing the well-to-wheels (WTW) exergy efficiencies of three vehicle technologies using natural gas, detailing both current operational efficiencies and theoretical maximums. It was found that vehicles powered by compressed natural gas (CNG) exhibit a WTW exergy efficiency of 31%, which is primarily impacted by losses within the internal combustion engines (ICEs), themselves operating at a current efficiency of 35%. In contrast, fuel cell vehicles (FCVs) achieve a WTW exergy efficiency of 25%, with considerable exergy loss occurring during the hydrogen reforming process and within the fuel cell engine itself, which operate at efficiencies of 69% and 50%, respectively. The percentages for FCEVs reflect the efficiency of hydrogen production from natural gas and the conversion efficiency of the fuel cell. Meanwhile, battery electric vehicles (BEVs) show the highest WTW exergy efficiency among the studied options at 44%. This efficiency, however, includes significant losses during the conversion of natural gas to electricity in combined cycle power plants, which have a current operational efficiency of 59%. In their comprehensive comparative LCA, Teimouri et al. [54] analyzed the environmental impacts of hydrogen fuel cell, electric, CNG, and gasoline-powered vehicles under real driving conditions. Utilizing the Simcenter Amesim Software for vehicle simulation and the GREET software for LCA, the study highlighted the superior performance of zero-emission vehicles, particularly electric and FCVs, in terms of energy efficiency and reduced pollutant emissions. The results underscored that FCVs and electric vehicles demonstrate a hopeful future in urban settings by significantly lowering CO_2, CO, NO_x, and SO_x emissions compared to their CNG and gasoline counterparts. This study provides crucial insights into the potential environmental benefits of adopting alternative fuel technologies in personal transportation, supporting the transition towards sustainable urban mobility. In a pivotal study by El Hannach et al. [3], the environmental and economic impacts of retrofitting heavy-duty class 8 trucks with dual-fuel systems that utilize both hydrogen and diesel were thoroughly assessed. Through a LCA, the study demonstrated substantial reductions in GHG and air pollutant emissions when integrating hydrogen into existing diesel-based fuel systems. The analysis, employing hydrogen as a partial substitute for diesel, showed potential cost savings due to the lower operational costs associated with hydrogen. This is particularly significant in the context of rising diesel prices and environmental compliance costs. The study also highlighted the feasibility of using low-cost waste hydrogen, thus presenting an economically viable bridge to more sustainable heavy-duty transport solutions. These findings underscore the dual benefits of such technological integrations in reducing emissions and operational costs, supporting a transition towards more sustainable heavy-duty freight systems. Although FCVs have a number of advantages over ICEs, Pei and Chen [55] showed in a separate study that there are significant barriers to their wider use. Significant obstacles were noted, including the high cost of fuel cell stacks, the shorter operational lifespan in comparison to ICEs, and the high costs of periodic maintenance. The adoption and practical use of FCVs are severely limited by these problems. Lohse-Busch et al. [56] conducted a comprehensive study on the Toyota Mirai, a standard FCV. Their research demonstrated that FCVs exhibit varied performance across different climate and driving scenarios. Specifically, they analyzed the vehicle's behavior across a temperature spectrum from −17 °C to 25 °C. Their findings indicated that the start-stop system utilized in the Toyota Mirai, designed to prevent hydrogen fuel from freezing under severe weather conditions, led to a significant increase in fuel consumption—up to 157% higher than in milder climates. This study underscores that similar to EVs, the efficiency of FCVs is heavily influenced by temperature variations, which can markedly impact their operational performance. In their detailed study, Shafique et al. [57] investigated the LCA of EVs and PHEVs alongside ICEs within the context of Hong Kong's evolving energy mix forecasted for 2025 through 2050. The study employed a comprehensive LCA to analyze the environmental impacts under current (2019) and future (2050) scenarios, revealing that EVs with the anticipated 2050 energy mix would offer the lowest environmental impact across several categories due to the planned substantial increase in renewable energy sources. Their analysis highlighted the pivotal role of the electricity source in determining the environmental effectiveness of EVs, illustrating that as Hong Kong transitions towards a greener energy grid, the overall environmental benefits of EVs improve significantly, positioning them as a preferable solution for mitigating urban transportation emissions. In their detailed exploration of the GHG impacts of electrified vehicles using a mix of renewable fuels, Andersson and Börjesson [58] provide a comprehensive LCA spanning hybrid, plug-in hybrid, and BEVs. The study meticulously evaluates these vehicles under various degrees of electrification, paired with a range of renewable fuels from bio-based ethanol to hydrotreated vegetable oil. Utilizing the 2020 European electricity mix for comparisons, the findings highlight that renewable fuels potentially offer greater reductions in life cycle GHG emissions than even low-carbon electricity mixes, thus challenging current policy biases towards electrification. This research underscores the necessity of adopting a diversified approach to fuel use within the transportation sector to meet rigorous climate targets effectively, advocating for adjustments in public policy to better support both electrification and renewable fuel utilization.

Finally, it should be noted that, on a long term basis, the efficiency of fuel cells will deteriorate and that could impact their emissions. Specifically, [69] modeled the challenges of old/degraded fuel cells for FCV manufacturers. Their findings indicate that a hydrogen vehicle with a degraded fuel cell consumes 14.3% more fuel than a fresh FCEV. Also, while a hydrogen vehicle with a degraded fuel cell emits lower CO_2 than a gasoline vehicle, the same vehicle (using hydrogen from electrolysis) emits approximately 25% more CO_2 than a hydrogen vehicle with new fuel cell.

2.3. Research gaps

A thorough review of earlier transportation-related studies that have taken LCA into account is shown in Table 3. The literature mainly focuses on the environmental impacts of different fuel types in private cars, disregarding public transit buses, which have unique environmental implications due to their high year-round usage and large passenger capacity.

Based on the literature review, the following research gaps are identified:

Table 3
Summary of studies on LCA, sustainability, and types of energy for public transportation.

References	LCA approach		Sustainability			Type of Transportation			Type of Energy								
	Manual Techniques	Software-Based LCA	Social	Economic	Environmental	General	Private	Public	Diesel	Biodiesel	Natural Gas	CNG	LNG	Hybrid (diesel–electric)	Hydrogen	Gasoline	Electric
[28]		✓			✓			✓	✓	✓		✓	✓	✓			
[59]	✓						✓				✓					✓	
[45]		✓		✓	✓		✓								✓	✓	
[44]		✓			✓	✓									✓		
[60]		✓			✓			✓	✓			✓	✓				
[51]	✓				✓	✓									✓	✓	
[33]		✓			✓			✓	✓	✓							
[61]		✓		✓	✓		✓								✓	✓	
[34]		✓			✓			✓						✓			
[62]		✓			✓				✓			✓					
[47]		✓			✓				✓			✓					
[53]	✓						✓					✓			✓		
[52]		✓			✓				✓						✓		
[49]					✓	✓			✓					✓	✓		
[50]		✓							✓						✓		
[30]		✓			✓			✓	✓								
[31]		✓			✓			✓	✓	✓	✓				✓		
[32]								✓							✓		
[63]		✓			✓			✓	✓						✓		
[64]		✓		✓	✓			✓	✓						✓		
[65]		✓		✓	✓			✓	✓				✓				
[66]		✓			✓				✓						✓		
[67]	✓			✓	✓			✓	✓								
[68]		✓			✓	✓			✓				✓				
[46]					✓										✓		
[35]	✓	✓			✓			✓	✓						✓		✓
[36]		✓			✓			✓	✓				✓		✓	✓	✓
[37]		✓			✓			✓	✓						✓		✓
[38]		✓			✓			✓	✓	✓					✓		✓
[39]		✓			✓			✓	✓						✓		✓
[40]		✓			✓			✓	✓						✓		
[41]		✓		✓	✓			✓	✓						✓		✓
[54]	✓	✓			✓		✓		✓			✓			✓	✓	✓
[56]	✓	✓			✓		✓								✓		
[57]		✓			✓		✓										✓
[58]		✓			✓			✓									✓
[42]	✓				✓			✓	✓						✓		✓
[43]		✓		✓	✓			✓	✓						✓		✓
This study	✓	✓	✓	✓	✓			✓	✓						✓		✓

- Despite numerous studies focusing on the environmental impacts of private vehicles, there is limited research on public bus transportation. In addition, such studies often relied on assumptions that render their results more theoretical than practical. As a result, there are limited studies based on real data.
- Utilizing new technologies, especially in transportation, necessitates a comprehensive evaluation of the entire transportation network to assess the advantages and disadvantages of these technologies compared to existing ones. Previous studies have typically analyzed single bus routes and generalized these results to entire transportation networks, which can lead to oversimplified conclusions.
- The number of LCA studies that address all aspects of sustainability for public transportation systems is limited. A comprehensive approach is needed to fully analyze all sustainability metrics when using LCA in the public bus system.
- There is a lack of studies that consider geographical conditions and resource availability, as well as operational uncertainties (e.g., number of passengers) in the LCA, especially in the operation phase. Such incorporation is absolutely necessary to ensure an accurate LCA and provide proper recommendations for policymakers in urban transportation sector.

To address the above gaps, this study discusses the findings of applying LCA in public bus transportation. The analysis is based on real data collected from a public bus transit system in Halifax, Canada, and existing manufacturing costs for different types of fuel and bus production in Canada. The next section describes the proposed research method.

3. Methodology

The proposed methodology in this paper adopts LCA as a crucial environmental assessment tool that evaluates the environmental impacts associated with a product or service throughout its entire life cycle. In this approach, each stage is entirely dependent on the previous stage. Fig. D.2 (in the supplementary material) shows the general structure of the LCA method.

The initial stage in LCA is to define the goals and the scope of the study. This crucial step sets the foundation for the entire analysis, establishing the purpose of the assessment, the intended audience, and how the results will be used. It also involves determining the system boundaries under study, specifying which processes and stages of the life cycle from the extraction of raw material to manufacturing, use, and disposal. In addition, this stage requires the identification of key environmental aspects, such as energy consumption, resource depletion,

Table 4
Specifications of various types of buses considered in this study.

Feature	Hydrogen bus	Electric bus	Diesel bus
Model	Xcelsior CHARGE FC™	Nova LFSe	Nova LFS Diesel
Passenger capacity	95	71	80
Battery capacity	360 kWh	564 kWh	–
Fuel tank capacity	39 kg (hydrogen)	–	473 l
Length (m)	12	12.2	12.19
Height (m)	3.35	3.35	3.20
Width (m)	2.6	2.6	2.59
Gross Weight (ton)	20	19.5	18.6
Approximate Cost ($)	1,200,000	750,000	510,000
Engine Type	Ballard FCmove-HD	TM4 Sumo HD electric powertrain 230 kW/2700 N m (308HP/1990 lb-ft)	Cummins L9 280
Turning Radius (m)	12.5	12.5	12.45
Structural Durability	16 Years	16 Years	16 Years

and waste generation, that are relevant to the analysis. The next stage, the life cycle inventory (LCI), is concerned with systematic compilation and quantification of all relevant inputs and outputs throughout the life cycle of the product, process, or service being analyzed. This includes data collection on raw materials, energy flows, air, water, and soil emissions, as well as the generation of solid waste. The LCI provides a detailed and comprehensive dataset that forms the basis for further analysis. Once the inventory is established, the Life Cycle Impact Assessment (LCIA) step evaluates the potential environmental impacts associated with the inputs and outputs identified in the LCI. This is done by classifying the data into established impact categories such as global warming potential, ozone layer depletion, acidification, eutrophication, and human toxicity. The LCIA translates inventory data into environmental impact indicators, facilitating a better understanding of the potential consequences of different stages of the life cycle. Finally, the Interpretation stage involves a critical review of the results obtained from the LCI and LCIA. This stage examines the reliability and significance of the findings, considering any uncertainties, assumptions, or limitations encountered during the analysis. It also involves insightful conclusions, helping informed decision-making processes and guiding the development of strategies to improve the environmental performance of the system under study.

3.1. Scope, goal, and boundary conditions

This section presents key definitions, scope, assumptions, goals, and the system boundaries of the model.

3.1.1. Definitions

Public transportation systems vary significantly in price and capacity, ranging from low-capacity options like taxis and minibuses to more expensive alternatives such as demand-responsive transport (DRT) and personal rapid transit (PRT) systems. Medium-capacity public transportation systems include light rapid transit (LRT) systems, buses, and trams. There are distinctions between urban, suburban, and inter-urban services, with heavy rail technology typically associated with high-capacity public transportation systems. This study focuses on various types of buses. Table 4 presents the specifications of each of the analyzed buses, including diesel, electric, and hydrogen-fueled buses.

3.1.2. Goal and boundaries

The goal of this study is to assess the environmental and economic advantages of employing advanced technologies, specifically electric and hydrogen buses, compared to traditional diesel buses in public transportation systems. Another crucial aspect of the LCA is establishing the system boundaries for the study. This determines the stages included in the analysis, ensuring that the modeling remains efficient. While Fig. 3 depicts the entire life cycle of a bus as assessed in this study, Fig. 2 illustrates the specific boundaries adopted for this study. The system boundaries of this study are categorized into two distinct sections: the energy cycle and the vehicle cycle. Given the evaluated vehicles utilize varying energy sources, it is essential to analyze their energy production pathways separately. Additionally, the vehicle cycle is pivotal in the LCA analysis, encompassing the manufacturing of components to the eventual scrapping of the vehicle.

3.1.3. Scope and assumptions

LCA is used to assess and compare the environmental impacts of different vehicle fuel types, including diesel, electric, and hydrogen. However, the challenge lies in the diversity of fuel options, as each has distinct production methods that influence its overall environmental footprint. These variations make it crucial to account for the entire life cycle, from fuel production to end use, to ensure an accurate and fair comparison. Considering this, the scope of this study is the environmental impacts and life cycle costs assessment of three distinct public bus technologies: hydrogen fuel cell buses, battery electric buses, and conventional diesel buses. The analysis considers multiple criteria, including emissions across the entire life cycle, energy efficiency, and long-term economic feasibility. To ensure consistency in the assessment, several assumptions are made. Fuel production methods for hydrogen include renewable energy-based electrolysis, natural gas reforming, and coal gasification, while electricity for battery electric buses is assumed to be sourced from the existing energy grid. The study accounts for variability in energy consumption due to route conditions, including factors such as road gradients, passenger loads, and stop frequency. The lifespan of all buses is assumed to be 16 years, without requiring mid-life battery replacement for hydrogen and electric buses. End-of-life disposal processes are considered, with a 30% material recovery rate for all types of buses. Infrastructure costs for hydrogen refueling, electric charging stations are not included in the analysis, while diesel infrastructure is assumed to remain unchanged. In addition, the functional unit of this study is defined as one passenger per kilometer traveled (passenger-km) by a public transit bus. This unit allows for a standardized comparison of environmental and economic impacts across hydrogen, electric, and diesel buses, considering variations in passenger capacity and operational efficiency.

3.2. Life cycle inventory and impact assessment

Fig. 3 presents the proposed framework for assessing the environmental impact and fuel consumption of buses (diesel, electric, hydrogen). In this framework, GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) software simulates the environmental impact of using alternative fuels in buses. GREET is a comprehensive software tool developed by the Argonne National Laboratory for evaluating the environmental impacts of various energy and transportation systems [70]. Primarily used for LCA, GREET enables researchers, policymakers, and industry professionals to estimate the GHG emissions, regulated pollutants, and energy consumption associated with different fuels, vehicles, and energy technologies. The software is particularly valuable for analyzing the full life cycle of energy systems, encompassing all elements from the extraction of raw materials to the production, transportation, and end-use of fuels and energy carriers. This includes a wide range of pathways for conventional and alternative fuels such as gasoline, diesel, ethanol, hydrogen, and electricity.

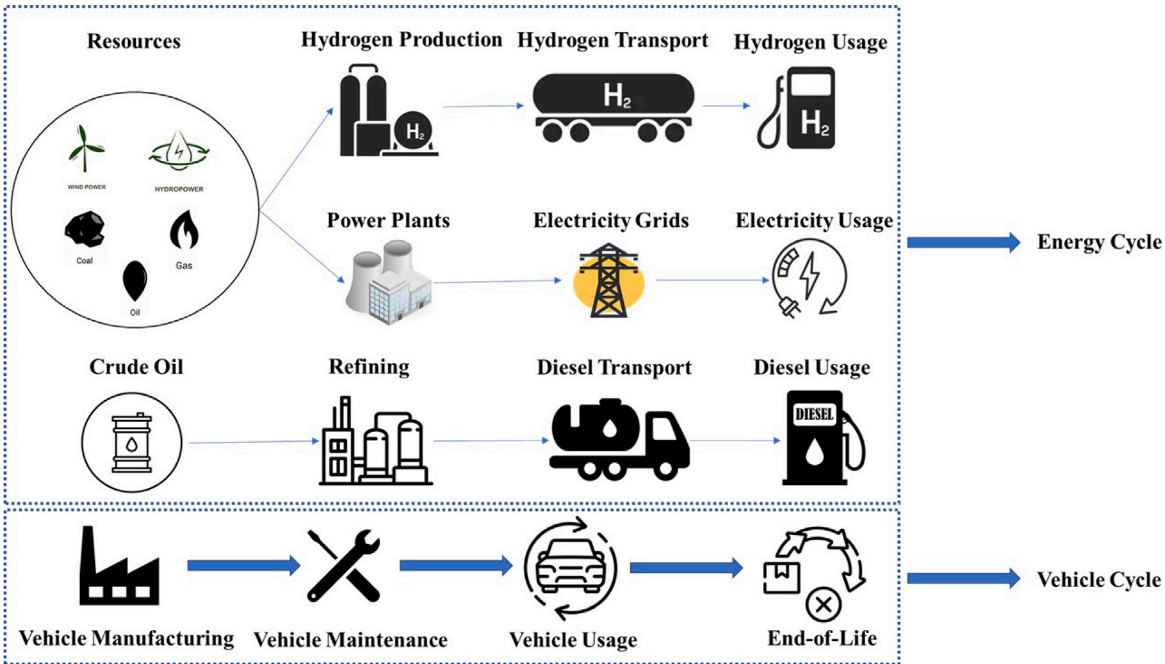


Fig. 2. System boundaries and the main stages of the vehicle and the fuel life cycles.

An urban bus system serves citizens across multiple routes. The costs of using different bus types make it challenging to upgrade all routes to new technologies or improve current ones within budget limits. Thus, a comprehensive life cycle cost (LCC) analysis of new technologies in the public transportation system, such as using hydrogen energy, should be conducted and compared with existing methods. In addition, it is essential to evaluate the future cost scenarios for the operation phase of buses due to the projected cost reduction in some technologies (e.g., hydrogen-based buses) [71]. Combining LCC with LCA allows decision-makers to balance cost-efficiency with environmental stewardship, ensuring a holistic evaluation of potential upgrades. Moreover, calculating and analyzing the energy consumption of each route is a crucial factor that can help decision-makers choose the most viable option. However, analyzing all routes, especially in mega-cities, can be challenging. To address this issue, machine learning techniques can provide an effective solution. In this study clustering, an unsupervised machine learning method, was applied to group the routes. After clustering, a representative route in each group was selected for calculating fuel consumption and CO_2 emissions. The list of equations for life cycle of energy, emissions, and cost analysis is provided in section A of the supplementary material.

4. Results and discussion

To validate the proposed framework in Fig. 3, a real dataset from Halifax, Canada, is utilized. The city is a popular destination for both Canadian citizens and immigrants, playing a significant role in its population growth. The projections indicate that Halifax's population will reach 650,000 by 2035 [72]. The Halifax Regional Municipality (HRM) has committed to achieving zero emissions by 2050, as outlined in its published net-zero plan [73]. According to this plan, Halifax needs to reduce its GHG emissions by around 1.4 $MtCO_2e$ by 2030, representing a reduction of nearly 75% compared to 2016 levels. To achieve this target, multiple sectors should contribute to the strategy. As the population increases, expanding the public transportation system by adding new buses becomes necessary. However, if diesel-powered buses continue to be used, the associated increase in pollution will directly conflict with the city's net-zero objectives. Therefore, exploring bus fleets with alternative fuels becomes crucial. The main question is which type of fuel is the most effective choice.

The HRM operates a public transportation system comprising 98 bus routes, serviced by approximately 369 conventional buses. Of these routes, 50 are classified as local and corridor routes, which are the primary focus of this study. Information about the bus routes, including gradients, elevations, and route numbers, is listed in Tables C1-C6 (please refer to the supplementary material). Additional details can be found on the HRM website [74].

4.1. Analyzing emission profiles

The CO_2 emissions for different fuel types — hydrogen (liquid and gaseous), diesel (produced in the US and Canada), and electricity — were compared across five production methods: Polymer electrolyte membrane (PEM), electrolysis using hydro and solar energy, high-temperature gas-cooled reactors (HTGR), coal, and renewable natural gas (RE-NG)(Fig. 4).

The results reveal key insights into the environmental impact of each type of fuel and production method, highlighting the varied potential for CO_2 reduction of emissions in public transportation. Hydrogen, considered a clean alternative fuel, exhibits significantly lower CO_2 emissions compared to diesel for all production methods. It was also noticed that the hydrogen production method plays a crucial role in determining its overall environmental impact. The lowest CO_2 emissions for liquid hydrogen are observed under PEM electrolysis using hydro energy, with an emission value of 0.000130 kg/passenger – km. This is the most environmentally friendly option that benefits from the zero-emission nature of hydroelectric power. On the other hand, hydrogen produced using coal emits the highest CO_2 at 0.000525 kg/passenger – km, more than four times the emissions from hydro-based production. This highlights the inefficiency and high environmental cost of coal-based hydrogen production.

RE-NG offers an intermediate level of emissions at 0.000377 kg/passenger – km, though still higher than renewable-based methods such as hydro and solar. Gaseous hydrogen emissions are consistently lower than liquid hydrogen among all production methods. The best performance is again seen with PEM electrolysis-hydro, with emissions of 0.000119 $kgCO_2 - eq/MJ$, reflecting the advantages of gas-phase hydrogen in terms of lower energy requirements for storage and distribution. Coal-based gaseous hydrogen production shows higher

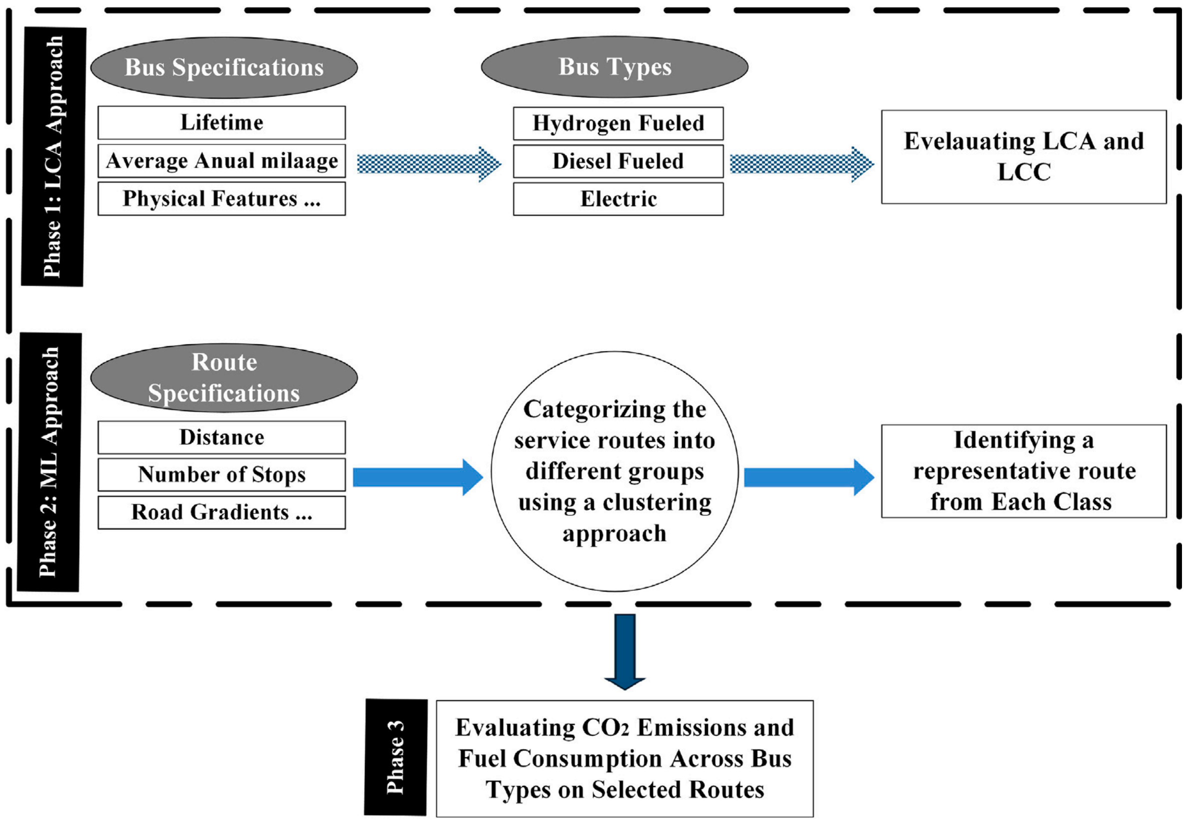


Fig. 3. Proposed framework for assessing the environmental impact and fuel consumption of buses with various technologies (diesel, electric, hydrogen).

emissions, reaching 0.000228 kg/passenger – km, though still significantly lower than its liquid counterpart, which suggests that gaseous hydrogen, regardless of production method, is a more efficient choice in terms of CO_2 emissions.

Diesel, produced in the US or Canada, demonstrates substantially higher CO_2 emissions compared to hydrogen and electricity. For diesel sources from the U.S. Diesel (US), the CO_2 emission is 0.001653 kg/passenger – km, and this value remains constant across production methods since diesel is a direct fossil fuel-based energy source. Diesel in Canada has slightly higher emissions at 0.001728 kg/passenger – km, reflecting differences in fuel composition or emissions standards between the two countries.

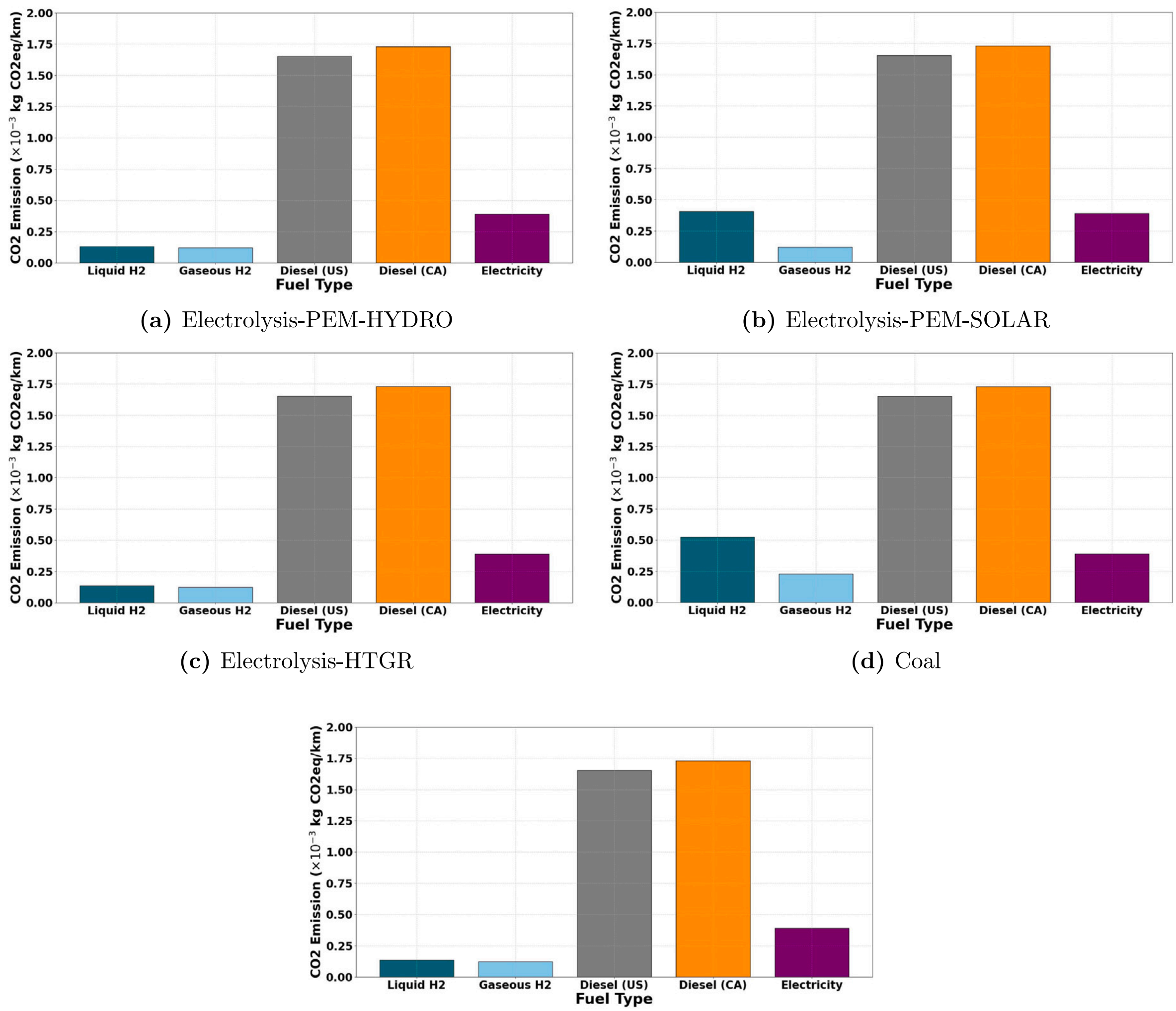
Even the most carbon-intensive methods of hydrogen production, like coal-based processes, result in significantly lower emissions compared to diesel. This suggests that the transition to hydrogen, even with less efficient production technologies, could still achieve significant CO_2 reductions in public transit systems.

The electricity used in electric buses also shows moderate emissions in all production methods, with a constant value of 0.000391 kg/passenger – km. Although electric buses exhibit lower emissions compared to diesel, their overall environmental impact heavily depends on the energy mix used in electricity generation. In this case, emissions are notably lower than those of diesel but higher than the most efficient hydrogen options, especially hydrogen produced through PEM electrolysis using hydroelectric power. Several key conclusions can be drawn by comparing the different fuel types and production methods:

- Hydrogen (PEM electrolysis with hydro energy) emerges as the most environmentally friendly option, particularly in its gaseous form. Its emissions are approximately 12.7 times lower than those of the US diesel and 14.5 times lower than Canadian diesel. This demonstrates the potential of hydrogen produced using renewable sources to significantly reduce CO_2 emissions in public transportation.
- Coal-based hydrogen production offers the highest CO_2 emissions among the hydrogen options, though still much lower than diesel. This highlights that while hydrogen is a cleaner fuel, the sustainability of its production process is critical to realizing its full environmental benefits.
- Electricity provides a moderately low-emission alternative, with emissions slightly higher than the best hydrogen options but still far superior to diesel. As grid decarbonization continues, electricity could offer increasingly substantial CO_2 savings.
- Diesel is clearly the most CO_2-intensive fuel option. Its consistently high emissions suggest that a transition away from diesel is necessary to meet environmental sustainability goals in public transportation. Even the least efficient hydrogen production methods present a cleaner alternative.

Table 5 summarize the GHG emissions analysis for the alternatives. The results for nitrogen oxides (NO_x) show that hydrogen-based fuels, particularly gaseous hydrogen, consistently produce lower NO_x emissions across all production methods compared to diesel. The lowest NO_x emissions are observed with PEM electrolysis using hydro energy, where gaseous hydrogen results in only 1.48E−07 kg NOx – eq. This is substantially lower than both the US diesel (4.59E−07 kg NOx−eq) and Canadian diesel (8.12E−07 kg NOx – eq). Diesel-based fuels have the highest NO_x emissions, and even electricity is comparable to diesel in terms of NO_x emissions. This suggests that transitioning to hydrogen, especially when using renewable energy sources for production, can lead to significant reductions in NO_x emissions, which are a major contributor to air quality degradation and respiratory problems.

For particulate matter (PM10 and PM2.5), hydrogen fuels again outperform diesel, particularly in gaseous form. The lowest PM10 emissions are observed for gaseous hydrogen produced using renewable natural gas, which yields just 1.67E−08 kg PM10 – eq, much lower than the US diesel (5.72E−08 kg PM10 – eq) and Canadian diesel (8.94E−08 kg PM10 – eq). Similarly, PM2.5 emissions from gaseous



(a) Electrolysis-PEM-HYDRO
(b) Electrolysis-PEM-SOLAR
(c) Electrolysis-HTGR
(d) Coal
(e) RE-NATURAL GAS

Fig. 4. Comparison of CO_2 pollution levels across the three presented bus technologies powered by various energy sources, considering different production methods.

hydrogen (R5) are the lowest among all alternatives, demonstrating the potential of hydrogen to reduce fine particulate matter, which is critical for improving air quality and reducing adverse health effects. Electricity-based fuels, on the other hand, have higher PM10 and PM2.5 emissions compared to hydrogen but still lower than diesel, making them a viable alternative.

Volatile organic compounds (VOCs) and sulfur oxides (SO_x) emissions also reveal that hydrogen fuels, particularly when produced via PEM electrolysis (hydro and solar), result in the lowest emissions. For VOCs, gaseous hydrogen (5.13E−07 kg VOC – eq) performs better than both the US diesel (6.39E−07 kg VOC – eq) and Canadian diesel (6.64E−07 kg VOC – eq). SO_x emissions follow a similar trend, with gaseous hydrogen (PEM-hydro) producing just 1.89E−07 kgSOx – *eq*, while diesel (US and CA) produces more than twice that amount. Coal-based hydrogen production, however, leads to the highest SO_x emissions among the alternative fuels, highlighting the importance of clean production methods in maximizing the environmental benefits of hydrogen fuels. Details of the LCA simulation results are provided in section B of the supplementary material.

4.2. Comparative analysis

This section compares this study's results with key findings from relevant literature. The LCA results presented here highlight that hydrogen-powered buses have a lower environmental impact than diesel and electric buses, particularly in terms of tailpipe emissions and long-term sustainability. According to the findings, replacing conventional diesel buses with hydrogen-powered alternatives can reduce CO_2 emissions by an average of 85%, while electric buses achieve an approximate 70% reduction. These results are consistent with those of Chang et al. [36] and Pederzoli et al. [40], both of whom reported that electric buses reduce GHG emissions by 45%–60% compared to diesel buses during operation. However, similar to the findings of Agostinho et al. [38], this study also identifies that battery production accounts for up to 40% of the total life cycle emissions of electric buses, raising concerns about the sustainability of large-scale battery manufacturing. In addition, Lubecki et al. [35] highlighted that the environmental impact of electric buses varies depending on the energy source used for electricity generation, with coal-based electricity increasing emissions by 60% compared to renewable-powered charging. The results of this study show that electric buses achieve a 51% reduction in life cycle CO_2 emissions compared to diesel buses, making them the most environmentally friendly option when charged with renewable energy sources.

Diesel buses consistently exhibit the highest life cycle emissions across reviewed studies. The findings of this study align with those of Jelti et al. [37] as well, who determined that diesel buses contribute 2–3 times more to GHG emissions, acidification, and particulate matter formation than electric and hydrogen buses. However, some studies, such as Ally and Pryor [31], suggest that diesel buses may emit up to

Table 5
Projected life cycle emissions of criteria air contaminants (CACs) for the studied bus types across different pollutants.

		E-PEM-HYDRO	E-PEM-SOLAR (or WIND)	E-HTGR	COAL	RE-NATURAL GAS
NO_x	Liquid H2	1.60E−07	3.70E−07	1.68E−07	4.44E−07	3.91E−07
	Gases H2	1.48E−07	1.48E−07	1.54E−07	2.16E−07	2.46E−07
	Diesel (US)	4.59E−07	4.59E−07	4.59E−07	4.59E−07	4.59E−07
	Diesel (CA)	8.12E−07	8.12E−07	8.12E−07	8.12E−07	8.12E−07
	Electricity	4.55E−07	4.55E−07	4.55E−07	4.55E−07	4.55E−07
PM10	Liquid H2	3.65E−08	6.70E−08	3.74E−08	1.66E−07	3.69E−08
	Gases H2	3.54E−08	3.54E−08	3.60E−08	1.27E−07	1.67E−08
	Diesel (US)	5.72E−08	5.72E−08	5.72E−08	5.72E−08	5.72E−08
	Diesel (CA)	8.94E−08	8.94E−08	8.94E−08	8.94E−08	8.94E−08
	Electricity	9.36E−08	9.36E−08	9.36E−08	9.36E−08	9.36E−08
PM2.5	Liquid H2	1.95E−08	3.67E−08	2.00E−08	5.16E−08	2.92E−09
	Gases H2	1.89E−08	1.89E−08	1.93E−08	3.28E−08	−7.52E−09
	Diesel (US)	3.74E−08	3.74E−08	3.74E−08	3.74E−08	3.74E−08
	Diesel (CA)	6.73E−08	6.73E−08	6.73E−08	6.73E−08	6.73E−08
	Electricity	5.05E−08	5.05E−08	5.05E−08	5.05E−08	5.05E−08
VOC	Liquid H2	5.15E−07	5.48E−07	5.16E−07	6.53E−07	3.55E−07
	Gases H2	5.13E−07	5.13E−07	5.14E−07	6.10E−07	3.46E−07
	Diesel (US)	6.39E−07	6.39E−07	6.39E−07	6.39E−07	6.39E−07
	Diesel (CA)	6.64E−07	6.64E−07	6.64E−07	6.64E−07	6.64E−07
	Electricity	5.65E−07	5.65E−07	5.65E−07	5.65E−07	5.65E−07
SO_x	Liquid H2	1.93E−07	3.70E−07	1.98E−07	5.48E−07	3.95E−07
	Gases H2	1.89E−07	1.89E−07	1.92E−07	3.54E−07	2.58E−07
	Diesel (US)	4.35E−07	4.35E−07	4.35E−07	4.35E−07	4.35E−07
	Diesel (CA)	6.72E−07	6.72E−07	6.72E−07	6.72E−07	6.72E−07
	Electricity	9.55E−07	9.55E−07	9.55E−07	9.55E−07	9.55E−07

20% less CO_2 than hydrogen buses when the latter is produced from fossil fuels. Despite this, most research, including this study, supports the phasing out of diesel buses, as they emit 70%–80% more CO_2 than hydrogen buses and 40%–60% more than electric buses, contributing significantly to urban pollution and climate change.

This research along with the literature discusses that the production method of hydrogen plays a crucial role in determining its overall life cycle emissions. In this study, it was found that hydrogen produced using a renewable-natural gas (RE-NATURAL GAS) pathway emits 40% more CO_2 than hydrogen generated via electrolysis using a proton exchange membrane (E-PEM-SOLAR). This finding aligns with those of Iannuzzi et al. [32] and Muñoz et al. [41], who emphasized that hydrogen derived from renewable sources, such as electrolysis powered by solar or wind energy, can reduce GHG emissions by up to 80% compared to hydrogen produced via steam methane reforming (SMR). Similarly, Grazieschi et al. [39] demonstrated that SMR-based hydrogen production results in 52% higher CO_2 emissions than renewable hydrogen production.

4.3. Sustainability index (SI)

The sustainability index evaluated GHG emissions as an important factor in demonstrating the benefits of alternative fuels compared to current technologies [45]. Eq.(1) is used to evaluate this index:

$$\text{Sustainability Index} = 1 - \frac{EA}{ER}. \quad (1)$$

In this equation, *EA* refers to the amount of pollution emitted during the entire life cycle (i.e., fuel and vehicle production, vehicle operation, and disposal stages) by the alternative fuels under consideration, while *ER* indicates the emission level of the base fuel used in public bus transportation. In this study, diesel is considered the conventional fuel used by buses, with electricity and hydrogen being evaluated as alternative options. Fig. 5 illustrates the value of the sustainability index.

The SI results highlight the relative environmental benefits of alternative fuel options compared to diesel, using a metric that accounts for the reduction in emissions relative to conventional diesel fuels. Comparing alternative fuels to diesel, the analysis reveals that gaseous hydrogen consistently has the highest sustainability index among all hydrogen production methods, particularly for PEM electrolysis with hydro energy at 0.9249. This demonstrates that gaseous hydrogen produced from renewable energy sources can substantially reduce GHG emissions, making it a highly sustainable option. Liquid hydrogen produced via coal has the lowest sustainability index at 0.6471, indicating that despite using hydrogen as a fuel, the production method significantly impacts its environmental benefits. Electricity shows a moderate sustainability index across all production methods, maintaining a value of 0.7505. It indicates that while electric buses are cleaner than diesel, the existing electricity production methods may limit their environmental advantages. While this study focuses primarily on the life-cycle sustainability of hydrogen buses, it is important to recognize that the scalability of such technologies is largely dependent on the availability of hydrogen infrastructure. The real world challenges encountered in the state of California or Tokyo highlight the complexity of establishing a comprehensive network of hydrogen refueling stations [75,76]. These examples refer to the challenges of facing significant hurdles, including the high costs associated with station construction and the logistics of transporting hydrogen, which can hinder the swift deployment of hydrogen fuel cell vehicles. Research indicates that the presence of refueling stations is a critical determinant of consumer adoption. The financial and logistical difficulties related to infrastructure development can substantially delay the broad adoption of hydrogen technology. Future research should investigate detailed infrastructure development models to better understand these barriers and offer practical solutions to overcome them.

4.4. Life cycle cost (LCC)

Fig. 6(a) provides a detailed analysis of the total cost of ownership (TCO) and major cost components for three bus powertrain options during their life cycles: diesel, electric, and FCVs. These cost categories encompass depreciation, fuel, diesel exhaust fluid (DEF) for diesel buses, maintenance, insurance, and licensing.

For diesel buses, the total cost is estimated at $2.80 million, with fuel costs representing the largest portion at $967,710. This is primarily due to the lower fuel efficiency and greater reliance on fossil fuels. Additionally, the cost of DEF, an essential emissions control additive, adds $17,570 to operational expenses. Maintenance costs for diesel buses are also substantial, reaching $1.13 million, reflecting the complexity and

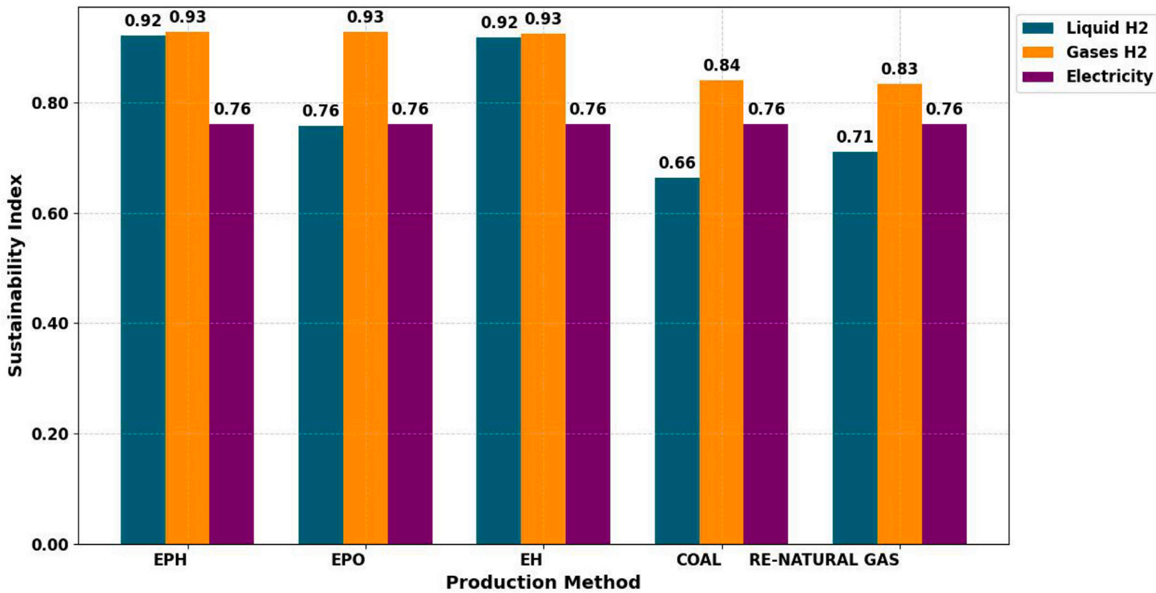


Fig. 5. Comparison of the SI for different hydrogen and electricity production methods.

wear and tear associated with internal combustion engines. Insurance costs stand at $248,059, while depreciation is $424,835.While depreciation is lower for diesel buses compared to electric and FCVs, this reflects their shorter expected useful life.

In contrast, electric buses have the lowest total cost at $2.10 million, underscoring potential cost savings during their life cycle. Electricity costs are significantly lower, at $427,484, due to the higher energy efficiency of an electric powertrain compared to an internal combustion engine. Maintenance costs are also reduced to $710,825. This is due to the simplicity of electric motors, which have fewer moving parts, resulting in less wear and tear. Depreciation for electric buses is higher than for diesel at $624,757; however, it remains lower than that of FCVs. The insurance cost for electric buses is $331,518, reflecting relatively more recent technology and the potential for higher replacement costs.

FCVs have the highest TCO, $4.08 million, which is 46% higher than diesel buses and almost double that of electric buses. FCVs also incur the highest fuel costs at $1.04 million, largely due to the expensive production and distribution of hydrogen fuel. Maintenance costs for FCVs are the highest among the three, reaching $1.54 million, due to the complexity of fuel cell systems and the need for specialized upkeep. Insurance for FCVs is also significantly higher at $488,003, attributed to the risks associated with more recent and less established technology. The depreciation cost for FCVs is the highest at $999,612, driven by their higher initial costs.

By comparing the TCO across these bus types, electric buses emerge as the most cost-effective option, with a TCO of $2.10 million. Diesel buses come second with a TCO of $2.80 million, largely driven by higher fuel and maintenance costs. In contrast, FCVs have the highest TCO at $4.08 million, due to the elevated fuel, maintenance, and insurance costs. Electric buses also offer significant savings in fuel costs, with expenses less than half of those for diesel and FCVs. Although diesel buses are more fuel-intensive, FCVs exhibit the highest fuel costs because of infrastructure and production expenses associated with hydrogen. Maintenance costs are lowest for electric buses, due to the simplicity of their motors, whereas FCVs demand the most maintenance due to their complex systems. Finally, FCVs also incur insurance and depreciation costs, reflecting the higher risks and expenses related to their advanced technology.

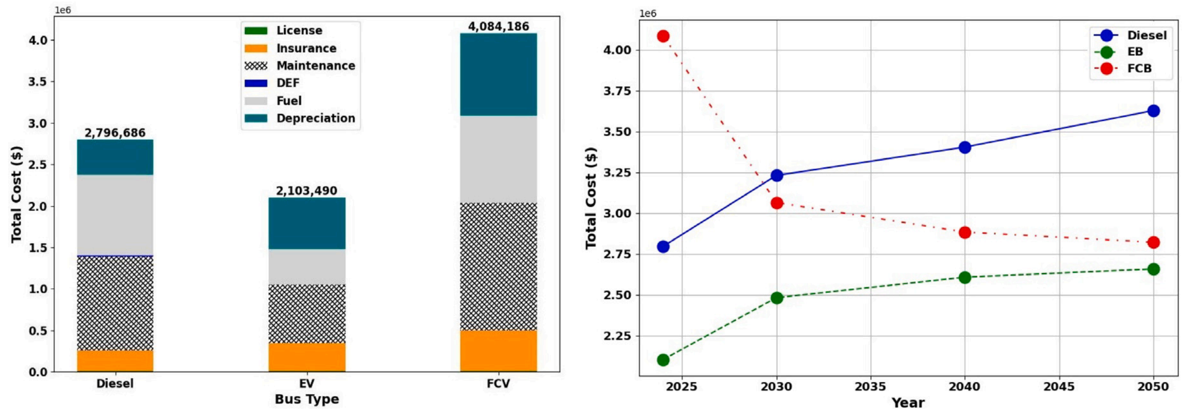
According to reports published by [77], which analyzed and projected fuel costs over the next 25 years, further advancements in technology and government policies aimed at environmental sustainability are expected to lead to a significant reduction in hydrogen prices, bringing them down to around $1.5 by 2050. In contrast, the cost of non-green fuels is projected to increase, potentially reaching around $4 to $5.

Based on these projections, Fig. 6(b) illustrates the LCC of the three buses under consideration. Hydrogen price reduction, results in a steady decline in the LCC of hydrogen buses, which converges with the cost of electric buses by 2050. On the other hand, diesel prices are anticipated to increase dramatically, potentially reaching $4 per liter, driven by dwindling supply, stringent regulations, and carbon pricing. This rise leads to a sharp increase in the LCC for diesel buses, making them the least cost-effective option by 2050. Electric buses, meanwhile, incur relatively stable costs over time because of improvements in battery technology and the increasing use of renewable energy. Although the total cost of electric buses rises slightly, it remains competitive with hydrogen buses, far outpacing the escalating costs of diesel buses. In total, the analysis highlights the long-term economic advantage of hydrogen and electric buses, with diesel becoming increasingly unsustainable under future fuel price scenarios.

It should be noted that incentive policies play a crucial role in promoting the use of green technologies [71]. To effectively address the impact of policy incentives on the adoption and cost reduction of hydrogen technologies, it is crucial to explore how measures like hydrogen tax credits and subsidies could be pivotal. Hydrogen tax credits help alleviate the financial burden on producers and consumers by offsetting a significant portion of the capital needed for hydrogen production facilities and fuel cell vehicles. This form of financial support makes hydrogen more competitive against conventional fuels, thus fostering greater adoption. Similarly, subsidies aimed at hydrogen production, particularly green hydrogen derived from renewable sources, can reduce operational costs and encourage market expansion. These subsidies often make up a part of the electricity expenses for electrolysis, which is the primary method for producing green hydrogen, thereby diminishing the total production costs. Moreover, government subsidies can help develop essential infrastructure, such as hydrogen refueling stations, which are vital for widespread adoption. Collectively, these policy initiatives can accelerate the transition towards a hydrogen economy, bolstering the viability of hydrogen as a sustainable alternative to traditional fossil fuels in urban transportation and beyond.

4.5. Fuel consumption rate

HRM uses 50 bus routes to serve the public. Since the main objective of this study is to analyze hydrogen energy use in public transportation



(a) TCO in 2025. (b) TCO from 2024 to 2050.

Fig. 6. Comparison of TCO across different powertrain types (diesel, electric, and fuel cell buses).

for various scenarios, evaluating all 50 routes in detail would be challenging.

4.5.1. Clustering bus routes

A machine learning approach is used to simplify the fuel consumption calculation while maintaining efficiency. Specifically, this study uses clustering, an unsupervised machine learning technique that groups similar data points based on certain characteristics. In contrast to supervised learning, where models are trained on labeled data, clustering algorithms operate on datasets without predefined labels, making them useful for exploratory data analysis. The primary goal of clustering is to identify natural groupings or patterns within the data, where data points within the same cluster share more similarities than those in other clusters. Common clustering methods include K-means, hierarchical clustering, and Density-Based Spatial Clustering of Applications with Noise (DBSCAN). This research applies K-means clustering as it is one of the most widely used methods. K-means partitions the data into a specified number of clusters by minimizing the variance within each cluster.

To determine the optimal number of clusters in this dataset, the Elbow method has been used. This method involves running K-means for a range of cluster numbers (typically starting from 1) and calculating the within-cluster sum of squares (WCSS) for each value of K. The WCSS measures the total variance within each cluster, which generally decreases as the number of clusters increases because adding more clusters typically results in smaller, tighter groups. The Elbow Method gets its name from the shape of the plot that results from graphing the number of clusters against the WCSS. In such plots, the WCSS sharply decreases at first as more clusters are added, but at a certain point, the rate of decrease slows down, creating a bend or "elbow" in the curve. This elbow point indicates the optimal number of clusters, where adding more clusters would no longer significantly reduce WCSS and would lead to diminishing returns.

Fig. 7 presents a comparison between the Silhouette Score and inertia for different numbers of clusters, helping to determine the optimal number of clusters for the data under analysis. The plot on the left illustrates the Silhouette Score, which measures the quality of clustering by assessing how similar an object is to its cluster compared to other clusters. The highest silhouette score is observed with two clusters, indicating a strong clustering quality, but the score sharply declines as the number of clusters increases, stabilizing around six clusters. This suggests that six clusters may provide a balance between cluster compactness and separation. The right plot depicts the Elbow method, which examines the total within-cluster sum of squares (inertia) as the number of clusters increases. A significant reduction in inertia is observed up to 6 clusters, after which the rate of decrease decreases, forming an elbow at six clusters. Both methods consistently suggest that six clusters represent the optimal balance between cohesion and separation, making it a robust choice for further analysis in the context of this study. After considering the optimal value of K=6, the optimal clusters have been illustrated by Fig. D.3 (please refer to the supplementary material).

Table 6
Details of selected routes from each group.

Route name	Route number	Distance (km)	Average daily passengers
Dartmouth crossing	56	29.7048	845.11
Dunbrack	30B	13.6497	338.88
Greystone	9A	26.5546	2936.87
Bedford commons	88	13.1087	125.96
Bedford highway	93	29.5715	157.07
Heritage hills	6C	24.3286	1004.84

4.5.2. Evaluating fuel consumption

To calculate fuel consumption for each type of route, the best route in each cluster was chosen as a representative (see Table 6).

To achieve this goal, the Virginia Tech comprehensive power-based fuel consumption model (VT-CPFM) was used to calculate the energy consumption for each type of bus [78]. Eq. (2) illustrates the structure of the VT-CPFM.

$$FCR(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2 & \text{for } P(t) \geq 0, \\ a_0 & \text{for } P(t) < 0. \end{cases} \quad (2)$$

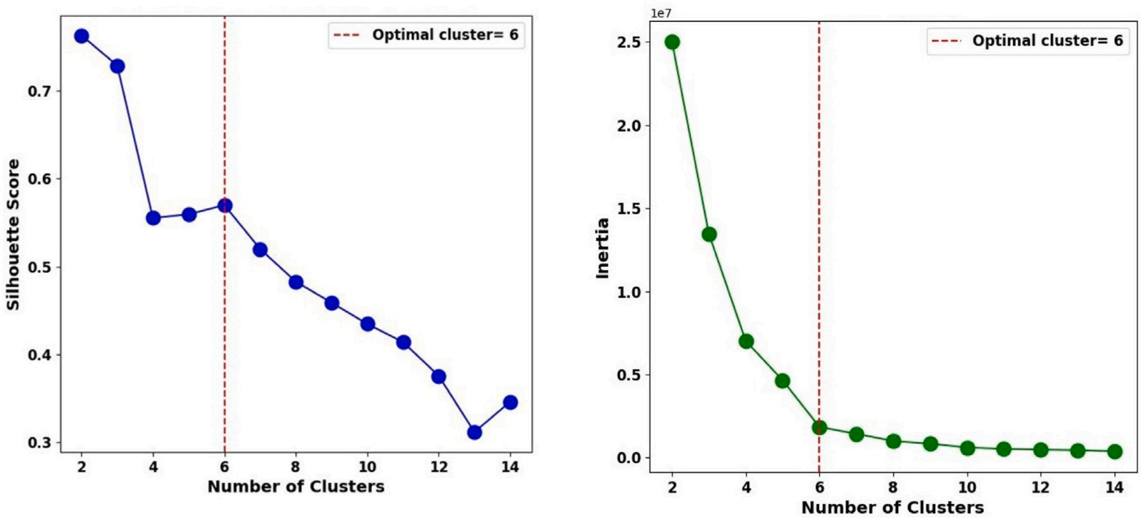
In this equation, $FCR(t)$ refers to the instantaneous fuel consumption rate, $P(t)$ represents the vehicle power (kJ), and a_0, a_1, and a_2 are the model coefficients. Moreover, to evaluate the value of $P(t)$, Eq. (3) can be used.

$$P(t) = \frac{R(t) + \left(1 + \lambda + 0.0025\zeta V(t)^2\right) ma(t)}{3600\eta} v(t). \quad (3)$$

In this context, $R(t)$ represents the vehicle resistance force in newtons (N). The parameter λ is the mass factor accounting for rotational masses, with a value of 0.1 being used for heavy-duty vehicles (HDVs). The factor ξ is assumed to be zero due to the lack of available gear data. The variable m represents the total mass of the bus, including both the curb weight and the passenger load, in kilograms (kg). The term $a(t)$ refers to the instantaneous acceleration measured in meters per second squared (m/s^2), while $v(t)$ is the vehicle speed in kilometers per hour (km/h). Finally, η denotes the drive line efficiency.

The vehicle resistance force $R(t)$ is the sum of the aerodynamic, rolling, and grade resistance forces, as described by Eq. (4).

$$R(t) = \frac{p_a}{25.92} C_D C_h A_f V(t)^2 + \frac{9.8066\, mC_r}{1000}\left(C_1 v(t) + C_2\right) + 9.8066\, mG(t). \quad (4)$$



(a) Silhouette Score. (b) Elbow method.

Fig. 7. Determination of optimal number of clusters using Silhouette Score and Elbow method.

Table 7
The value of the parameters used in the fuel consumption analysis.

	Hydrogen bus	Electric bus	Diesel bus
λ	0.1	0.1	0.1
η	0.92	0.9	0.85
C_D	0.6	0.6	0.8
C_h	1	1	1
A_f	7.5 m^2	7.5 m^2	7.5 m^2
ρ_a	1.2256 kg/m^3	1.2256 kg/m^3	1.2256 kg/m^3
m	20	19.5	18.6
C_r	0.007	0.007	0.007
C_1	0.01	0.01	0.01
C_2	0.001	0.001	0.001

Here, ρ_a denotes the air density at sea level at a temperature of 15 °C (59° F), with a value of 1.2256 kg/m^3. The variable C_b stands for the drag coefficient of buses, which is dimensionless. The altitude correction factor H is also dimensionless and is calculated using the formula $1 - 0.085H$. In addition, H indicates the elevation in km. The parameter A_f corresponds to the frontal surface area of each bus, expressed in square meters (m^2). The function $G(t)$ describes the road grade at any moment, derived from elevation profiles. Lastly, C_r, C_1, and C_2 are dimensionless parameters for rolling resistance. Tables 7 shows the value of each parameter for each type of bus.

Moreover, Fig. 8 shows the real-time profiles of $altitude$ and $v(t)$ for six selected bus routes. Route 10 is also included because of its importance for HRM.

Finally, Fig. 9 shows the predicted fuel consumption rates for each type of bus on the selected routes. The results of all routes revealed that diesel buses have the highest level of energy consumption, while electric buses have the lowest amount. Hydrogen-fueled buses exhibit behavior almost similar to that of electric buses. The reason for the lower fuel consumption in electric buses is primarily due to their significantly lower weight compared to diesel and hydrogen buses, which reduces their energy demand. In addition to weight, aerodynamic properties and drive line efficiency contribute to the variations in fuel consumption. Diesel buses, with their larger mass and lower efficiency, consistently show higher average fuel consumption across all routes, with the highest average consumption recorded on Route 93 at 0.003329 kJ/passenger−km. Hydrogen buses, while more efficient than diesel buses, still consume more fuel compared to electric buses due to their relatively higher mass. However, electric buses demonstrate the best performance, with average fuel consumption ranging from 0.001421 kJ/passenger – km on Route 10 to 0.002329 kJ/passenger – km on Route 93, highlighting their suitability for routes with varying terrain and conditions.

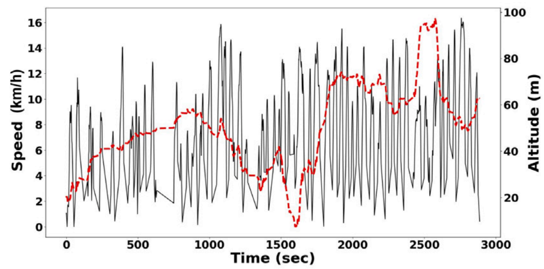
The data suggest that, given the current technologies used in hydrogen and electric buses, electrification of bus fleets offers significant fuel savings compared to hydrogen and diesel, especially on routes with higher fuel demands such as Route 93 and Route 88.

4.6. Sensitivity analysis on energy consumption

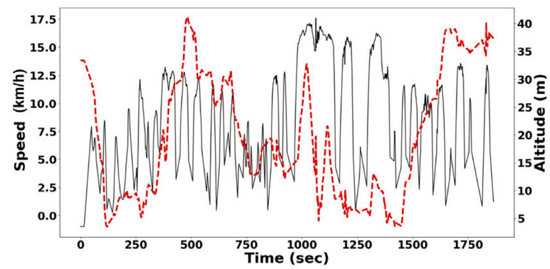
To demonstrate the sensitivity of the model to geographic variations in energy consumption, the model was simulated for four different scenarios: (1) short route-high elevation, (2) long route-high elevation, (3) short route-low elevation, and (4) long route-low elevation. The obtained values were compared with those from the case study, where routes 56 (longest distance) and 88 (shortest distance) were selected as reference points.

As shown in Fig. 10, energy consumption varies significantly based on both altitude and distance, with diesel buses consistently exhibiting the highest energy consumption across all scenarios. The results indicate that in high-altitude regions, energy demand is significantly higher across all fuel types due to the additional energy required for propulsion on steeper inclines. This effect is particularly pronounced for long mountainous routes, where energy consumption increases by +40% for diesel, +32% for hydrogen, and +27% for electric buses compared to the reference case. The high energy demand for diesel buses can be attributed to their inefficiencies in internal combustion and the lack of regenerative braking, which leads to excessive fuel consumption on steep terrains. Similarly, hydrogen buses also show considerable energy demand due to fuel-cell conversion losses, making them less efficient than electric alternatives in such conditions.

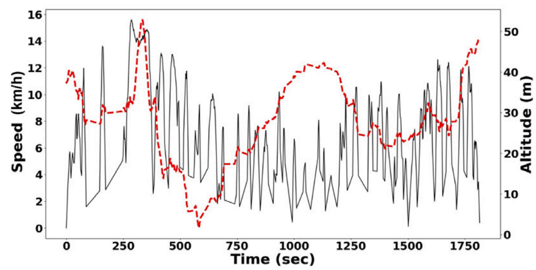
Conversely, in low-altitude flat terrains, energy consumption decreases significantly across all fuel types, particularly for short routes. Compared to the reference case, energy demand drops by −45% for diesel, −48% for hydrogen, and −41% for electric buses on short, flat routes. This reduction is primarily due to the lower resistance forces, more stable speeds, and efficient regenerative braking in electric and hydrogen buses. The results confirm that electric buses remain



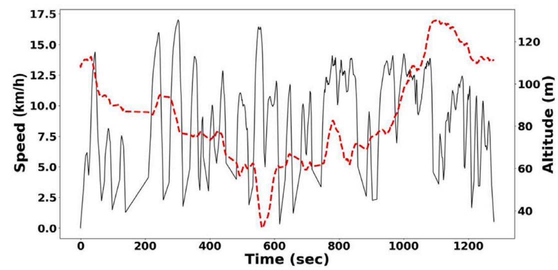
(a) Route Number 9A.



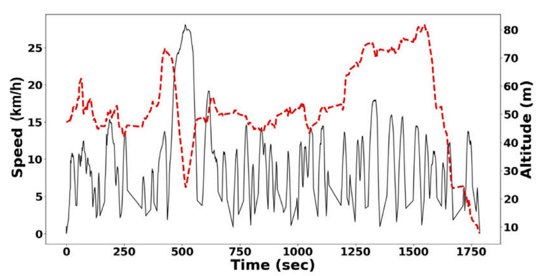
(b) Route Number 6C.



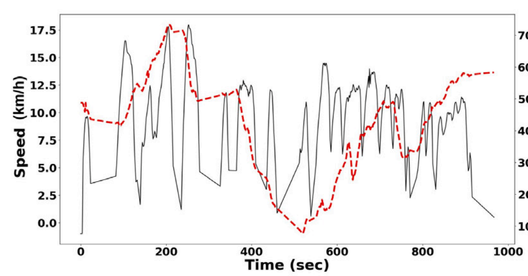
(c) Route Number 10.



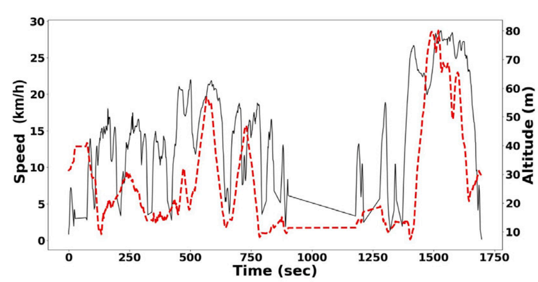
(d) Route Number 30B.



(e) Route Number 56.



(f) Route Number 88.



(g) Route Number 93.

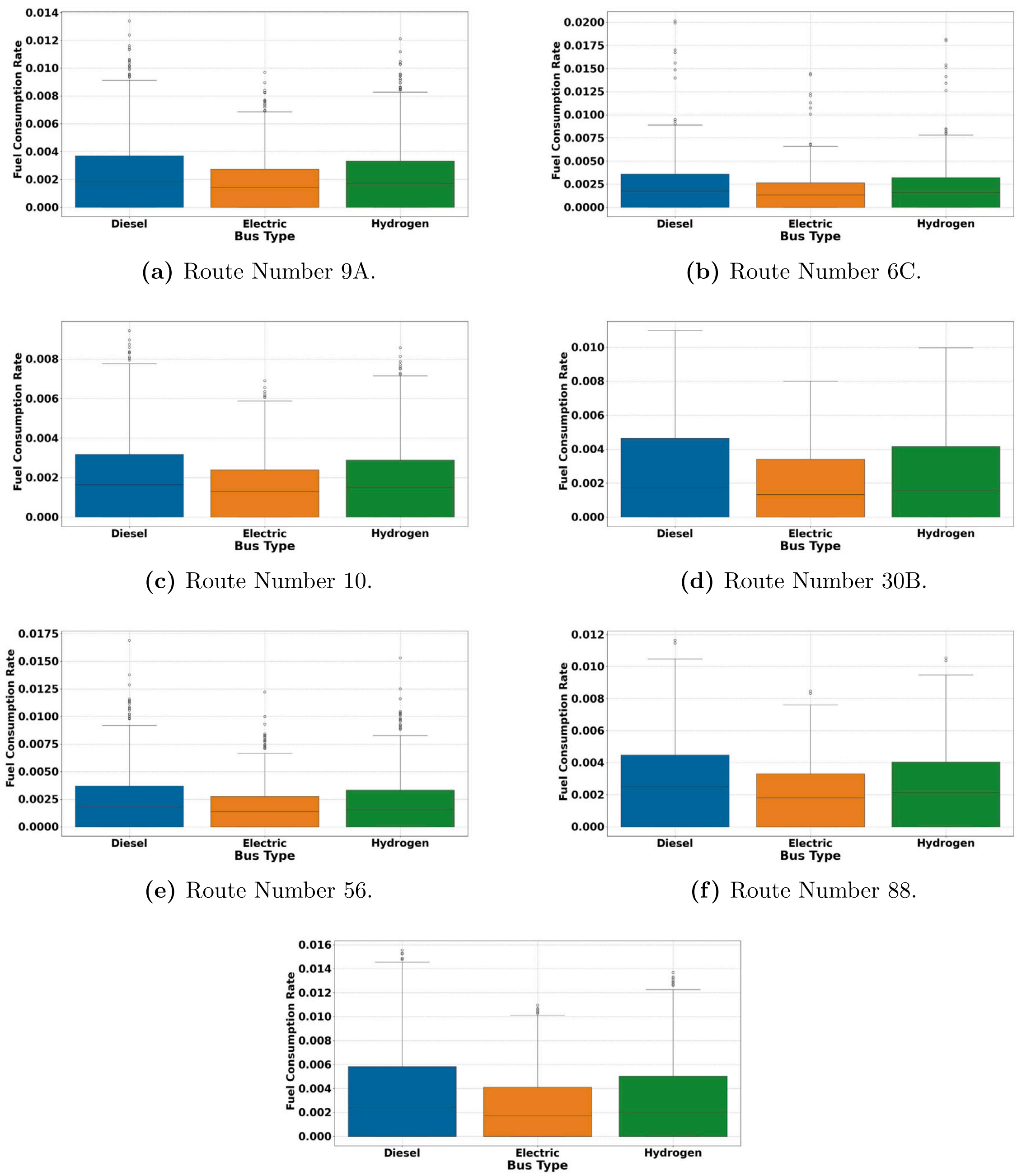
Speed (m/s) — — Altitude (m)

Fig. 8. Real-time speed and altitude data for selected routes.

the most energy-efficient option across all scenarios, particularly on short-distance and flat routes where their regenerative braking capabilities and direct energy use efficiency minimize total consumption. For long-distance routes in flat areas, energy consumption still follows a decreasing trend, though to a lesser extent. The reductions are −25% for diesel, −28% for hydrogen, and −35% for electric buses, indicating that longer distances inherently require more energy, but the absence of steep inclines still makes these conditions significantly more favorable than mountainous routes.

These findings emphasize the importance of considering geographical factors when selecting fuel types for public transit systems. While electric buses are the most energy-efficient in all cases, their battery capacity limitations make hydrogen a more viable option for long-haul routes. Meanwhile, diesel buses, which consistently exhibit the highest energy consumption, should be phased out, particularly in high-altitude, long-distance routes, where their inefficiency is most evident.

The proposed framework can be applied to other regions with different geographical conditions, policies, and fuel technologies. For cities lacking hydrogen infrastructure, the methodology can be adjusted to analyze the feasibility and impact of introducing such technologies, supported by incentive policies like tax/subsidy to encourage future developments. Regions with a higher penetration of renewable energy sources might see different cost-benefit outcomes, which the proposed framework can evaluate by adjusting the parameters of the energy mix.



(a) Route Number 9A. (b) Route Number 6C. (c) Route Number 10. (d) Route Number 30B. (e) Route Number 56. (f) Route Number 88. (g) Route Number 93.

Fig. 9. Real-time fuel consumption rate for selected routes.

This flexibility ensures the relevance of the model in diverse urban settings, facilitating tailored sustainable transit solutions.

4.6.1. Carbon emission and equity analysis

Assessing equity in public transportation, in terms of emissions, is crucial for ensuring that the benefits of adopting cleaner technologies, such as hydrogen and electric buses, are fairly distributed among transit users. To achieve this goal, a sensitivity analysis is conducted on the amount of CO_2 emissions for each service route by considering different average numbers of passengers per trip.

Fig. 11 shows the variation in CO_2 emissions for all types of buses across different numbers of passengers for each driving cycle. While the transition to low-carbon transit is often evaluated based on total emission reductions, it is equally important to examine how these reductions are allocated across different routes and passenger groups. In this study, we introduce an equity-based approach to evaluating emissions per *passenger-kilometer* by incorporating the Gini coefficient, a widely used metric for measuring inequality, originally proposed by Corrado Gini [79]. By analyzing emissions distribution across various bus technologies (diesel, hydrogen, electric) and transit routes, this section aims to quantify whether certain routes or communities bear a disproportionate environmental burden. This insight not only enhances the sustainability assessment of alternative bus technologies but also provides a foundation for policy recommendations that promote environmental justice and equitable access to clean transportation.

As per the regulations of relevant United Nations organizations [80, 81], a Gini coefficient below 0.2 signifies an “absolutely equal” distribution. Values between 0.2 and 0.29 indicate a “relatively equal” state, while a range of 0.3 to 0.39 is considered "relatively reasonable”. A

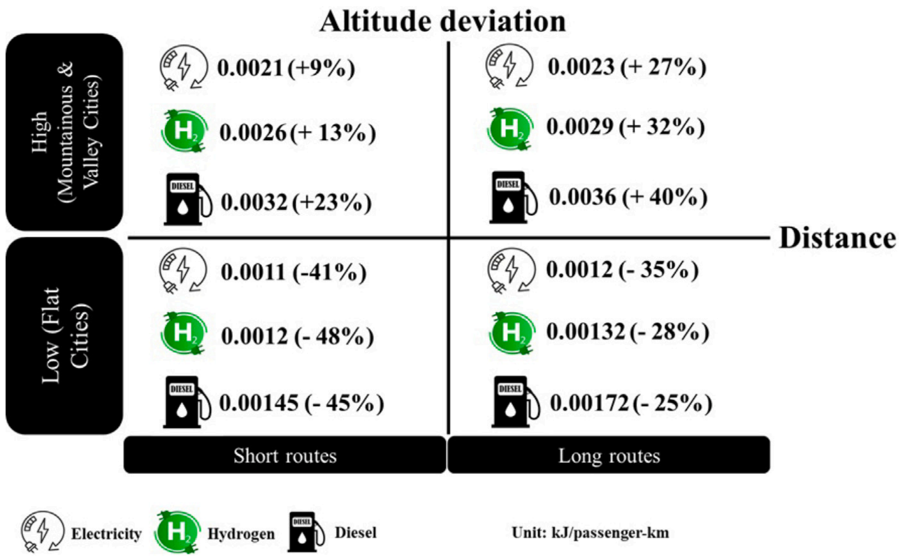


Fig. 10. Energy consumption across different geographical scopes for each type of bus, compared to routes 88 (shortest) and 56 (longest) from the case study.

Table 8
Details of CO_2 emission for selected routes from each group.

	Hydrogen bus ($kgCO_2$/ $passenger-$km)	Electric bus ($kgCO_2$/ $passenger-$km)	Diesel bus ($kgCO_2$/ $passenger-$km)
Route 56	0.005052	0.016603	0.073360
Route 30B	0.013545	0.044514	0.196686
Route 9A	0.001064	0.003498	0.015456
Route 88	0.034701	0.114041	0.503894
Route 93	0.031792	0.104483	0.461660
Route 6C	0.004123	0.013550	0.059872
Route 10	0.000895	0.002943	0.013003

threshold of 0.4 is typically regarded as a "warning line" for inequality. When the coefficient falls between 0.4 and 0.49, it suggests significant disparities among evaluation objects, and a value exceeding 0.5 indicates a highly unequal distribution. Eq. (5) shows the considered Gini coefficient formula used in this study.

$$G = \frac{2}{N^2 \bar{E}} \sum_i \sum_j \left| E_{\mathrm{eq},i} - E_{\mathrm{eq},j} \right|, \tag{5}$$

where N represents the total number of route–bus combinations, $E_{eq,i}$ denotes the emissions per *passenger-kilometer* for each route–bus combination, and $\bar{E}$ is the average emissions per *passenger-kilometer* across all routes and bus technologies. By using the road features of the selected seven routes from previous studies, the amount of CO_2 emissions per passenger is shown in Tables 8.

By evaluating Eq. (5) by using values of this table, Gini coefficient will be 0.52. This value indicates a moderate to high level of inequality in CO_2 emissions per *passenger-km* across different bus technologies and transit routes. This suggests that certain routes and bus types contribute disproportionately to total emissions, which can be attributed to several key factors, including differences in road gradients, traffic congestion, passenger load variations, and the reliance on conventional diesel buses in specific areas. Notably, routes with steeper inclines or lower passenger occupancy tend to exhibit higher per-passenger emissions, exacerbating disparities in environmental impact. This finding has significant implications for transit planning and environmental equity, as it suggests that some communities may be more exposed to transit-related emissions than others, particularly if high-emission routes pass through densely populated or socio-economically disadvantaged areas. To address this imbalance, strategic deployment of low-emission buses on high-emission routes is recommended, particularly for corridors with high passenger demand or substantial pollution levels. Overall, the moderate-to-high Gini coefficient observed in this study underscores the necessity of targeted policy interventions to enhance environmental equity in public transportation networks, ensuring that the benefits of transitioning to cleaner bus technologies are equitably distributed across all transit users and communities.

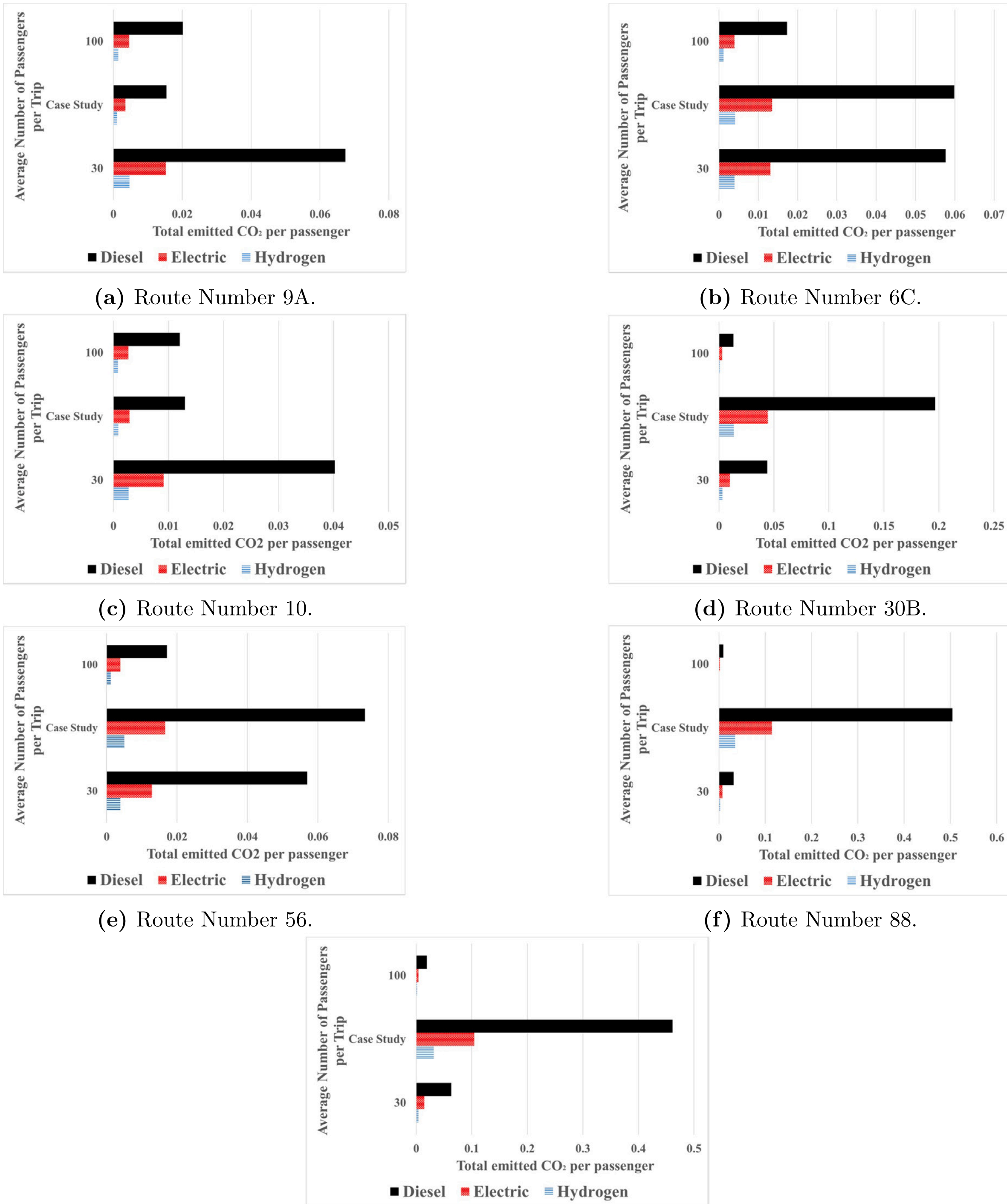
5. Managerial insights

The analyses conducted in this study provide important managerial insights helping transit authorities, policymakers, and industry stakeholders in strategic decision-making for sustainable public transportation.

First, the LCA results highlighted that hydrogen-fueled buses have a lower overall environmental impact rather electric and diesel buses, particularly when considering both the production and salvage stages. While hydrogen buses emit zero emissions during operation, most of their environmental impact arises from the fuel production stage. This underscores the importance of developing cleaner hydrogen production technologies to fully realize their environmental benefits. For governments aiming to enhance the sustainability of public transportation, investing in greener hydrogen production methods should be a priority.

Second, the LCC analysis revealed that current hydrogen bus technologies remain significantly more expensive than electric and diesel alternatives. The high costs associated with hydrogen production, storage, and vehicle manufacturing pose financial challenges for large-scale adoption. Additionally, this study assumes that technological requirements for all energy types are already in place, eliminating the need for further investments, which would otherwise have an additional impact on the cost analysis. However, long-term projections indicate that hydrogen costs will decline as production efficiency improves and economies of scale are achieved. Policymakers must consider both immediate cost constraints and future cost trajectories when making investment decisions.

Third, beyond cost and environmental considerations, strategic route planning and operational efficiency play a crucial role in maximizing the benefits of alternative fuels. The machine learning-based clustering method employed in this study demonstrates how transit agencies can optimize fuel-efficient deployment of electric and hydrogen buses by identifying route-specific energy demands. Electric buses are better suited for shorter urban routes with existing charging infrastructure, whereas hydrogen buses can provide a more reliable alternative for longer-distance or high-frequency corridors. Integrating



(a) Route Number 9A.

(b) Route Number 6C.

(c) Route Number 10.

(d) Route Number 30B.

(e) Route Number 56.

(f) Route Number 88.

(g) Route Number 93.

Fig. 11. Total CO_2 emissions for different numbers of passengers during service time.

data-driven decision-making into fleet transition strategies will enable transit regulators to minimize energy consumption and improve cost-effectiveness while maintaining service reliability.

Fourth, the successful adoption of alternative fuel buses hinges on the availability of adequate refueling and charging infrastructure. Municipal authorities and private sector stakeholders should collaborate to expand the hydrogen refueling network and increase charging station accessibility in strategic locations. Additionally, incentive programs, tax credits, and subsidies for clean energy transit investments will accelerate adoption and improve cost parity with conventional diesel fleets. Given the rapid advancements in battery storage and hydrogen production technologies, policymakers should also implement flexible policies allowing for future technological integration and adaptation.

Fifth, environmental and social equity considerations should also be factored into public transportation decisions. While transitioning to low-carbon transit is often assessed based on total emissions reductions, it is equally important to evaluate how these benefits are distributed among different communities. The equity analysis in this study suggests that emission reductions should be fairly allocated across transit routes to prevent certain communities from experiencing disproportionate pollution exposure. Decision-makers should integrate environmental justice principles into transit planning by ensuring that alternative fuel buses are deployed in high-density areas where vulnerable populations are more likely to rely on public transit.

6. Conclusions

In this research, the economic and environmental implications of adopting alternative types of fuel in public transportation services were thoroughly examined. The proposed framework was validated using the data from Halifax, Canada, and further analyzed to include other geographical scopes and operation conditions. Using GREET software to simulate the environmental impacts of hydrogen, electric, and diesel buses, the results indicate that hydrogen buses generally emit the lowest levels of pollution, particularly gaseous emissions. Moreover, the method of fuel production plays a crucial role; for instance, hydrogen produced via coal or electrolysis-PEM-solar methods can emit higher CO_2 levels compared to those from electric sources. Furthermore, the life cycle cost (LCC) of these buses was evaluated, revealing that hydrogen buses have higher costs than other alternatives. However, it was also realized that if governments impose stricter environmental regulations and support hydrogen usage, advancements in production methods and reductions in hydrogen fuel costs coupled with increases in diesel prices could significantly lower the LCC of hydrogen buses, enhancing their economic feasibility. Finally, by applying the VT-CPFM framework, the energy consumption rates for each type of bus were calculated based on real-time GPS data. The analysis results indicate that hydrogen and electric buses exhibit comparable and more efficient energy consumption rates than diesel buses. Despite this, the higher weight of hydrogen buses currently leads to slightly less efficient performance than electric buses. Overall, although the environmental impacts of using hydrogen fuel buses are lower than those of electric and diesel buses, according to economic and energy consumption perspectives, they are not yet on par with electric options. However, it is anticipated that with further enhancements in production technologies, hydrogen buses can achieve energy consumption rates comparable to those of electric buses.

Beyond environmental and economic factors, the equity analysis in this study underscores the need to prioritize alternative fuel buses on routes serving high-density and vulnerable communities to mitigate disproportionate pollution exposure. Policy development plays a crucial role in ensuring the successful adoption of low-carbon transportation solutions. Governments can implement regulatory incentives, such as subsidies for hydrogen and electric buses, carbon pricing mechanisms, and zero-emission transit mandates, to encourage the transition to sustainable public transportation. Infrastructure investment is also critical, as the expansion of charging stations and hydrogen refueling facilities directly impacts the feasibility of large-scale implementation. Furthermore, public transit regulators should integrate LCA insights into long-term sustainability planning, ensuring that economic and technological considerations align with environmental goals. By fostering collaboration among policymakers, transit operators, and industry stakeholders, these policy directions can facilitate a more efficient and environmentally responsible public transportation network.

Although this study provides significant insights into the environmental and economic impacts of hydrogen-fueled, electric, and diesel buses, several limitations exist. Firstly, the data used in the LCA are subject to availability and are specific to particular regions, which may limit their applicability to other geographic contexts. Additionally, the LCA model relies on assumptions regarding bus operation conditions, fuel usage, and maintenance that may not fully reflect real-world scenarios. Furthermore, factors such as fuel price volatility, influenced by various external conditions, can directly impact the measurement of life cycle cost (LCC), adding another layer of complexity. Lastly, the rapid advancement in alternative fuel technologies suggests that the findings need uncertainty involvement, underscoring the need for continuous updates to the LCA data to reflect the latest technological improvements.

For future studies, it would be pertinent to consider seasonal effects on energy consumption, as these can vary significantly between summer and winter due to differences in heating and cooling needs and overall operational efficiency. Investigating how bus technologies respond to these seasonal changes would provide deeper insights into optimizing fuel usage and improving the overall sustainability of public transportation systems. It is also essential to examine various sources for producing hydrogen and electricity, as this study demonstrates that different production methods can significantly influence their environmental impacts. Moreover, establishing new charging stations and using new technologies will add additional costs, which will increase the LCC. Therefore, it seems critical to consider these challenges in simulations for different fleet sizes as well. Subsequently, integrating the results of this study with other optimization methods and strategies, such as analyzing consumer behavior regarding the use of green versus non-green public transportation, as well as government policies, could provide a subsequent step. This approach can offer valuable insights to decision-makers in terms of long-term planning aimed at achieving net-zero targets. In addition, it should be noted that several factors can impact public transportation pollution, such as population fluctuations, which can cause heavy traffic congestion and affect passenger loads. Thus, considering methods such as System Dynamics (SD) can help explore these factors and integrate them with LCA methods. SD models can capture feedback loops, time-dependent changes, and interactions between transportation demand, infrastructure development, and emissions. By combining SD with LCA, one can dynamically assess how policy changes, urban expansion, and travel behavior influence the long-term environmental impacts of public transportation systems, leading to more effective decision-making for sustainable transit planning. Although the Gini Coefficient effectively measures emissions disparities, it does not capture broader equity aspects, such as accessibility to low-emission buses for low-income communities. The Gini Coefficient can be extended to include socio-economic factors such as transit affordability and population density. Future studies could incorporate accessibility indices and demographic data for a more comprehensive equity assessment.

CRediT authorship contribution statement

Ali Mahmoudi: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Hamid Afshari:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Hassan Sarhadi:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Resources . **Armin Jabbarzadeh:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Resources.

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. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.03.316.

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