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Review

Fuel Cell Electric Buses: A Systematic Literature Review

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Abstract: This paper presents a comprehensive review of scientific papers and market reports analyzing the economic competitiveness of fuel cell electric buses (FCEBs) with respect to their conventional alternatives via the total cost of ownership (TCO) methodology. We discussed the variables and data taken into account and compared the resulting outcomes by year and geographical areas. It emerged that FCBs are not currently cost competitive. The decreasing trend in acquisition and fuel costs, however, indicates potential for future competitiveness. We find that the current TCO literature on FCEBs presents several areas of uncertainty and weakness. Potential improvements can be achieved by: (i) extending the geographic coverage to Asian and African developing countries; (ii) making use of real-world data instead of simulated data, in particular, concerning acquisition costs, hydrogen costs under different pathways, fuel efficiency, and maintenance costs; (iii) clarifying the role of infrastructural costs; (iv) exploring the existence of economies of scale at fleet level; (v) distinguishing among different bus sizes.

Keywords: hydrogen-powered buses; total cost of ownership; systematic review; diesel-powered buses

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1. Introduction

Fuel Cell Electric Buses (FCEBs) help reduce the emissions of local pollutants in urban and peri-urban areas and greenhouse gas emissions. For this reason, their technical, environmental and economic characteristics have been the focus of attention for more than a decade [1,2]. According to reference [3], as of June 2023, some 7000 fuel cell buses were operational worldwide, 85% of which were in China, but also in Europe, the Republic of Korea, the United States and Japan.

In Europe, FCEBs have been the subject of experimentation in multiple European projects, recently reviewed by reference [3] on behalf of the EU Joint Research Centre (JRC). The technical KPIs of FCEBs—such as operational fuel cell system durability, total hours of operation, and hydrogen consumption per 100 km driven—and the fact that they have been deployed in many European cities for at least 17 years (2005–2022), thus accumulating a mileage of more than 17 million km, demonstrate the readiness of the FCEB technology. Data on the economic features are scarcer. Reference [3] reports some values and forecasts concerning maintenance costs (spare parts and labor), operational fuel system costs and bus costs, but does not include data concerning their Total Cost of Ownership (TCO).

The TCO is, however, crucial in understanding the present and future penetration of FCEBs, relative to alternative technologies. First and foremost, with respect to buses equipped with internal combustion engines, fueled by diesel or methane gas, but also with respect to electric buses, which are seeing increasing market penetration.

The purpose of this article is to review the studies presented to date in scholarly journals and non-referenced research reports (grey literature) in order to compare their results and the data used to estimate the current TCO and, prospectively, the probable evolution of the future TCO.

Since FCEBs are at the initial stage of development and experimentations, to the best of our knowledge, there are no recent and detailed reviews of the TCO estimates available in the literature. We aim to fill in this gap with this article. The results of the review can be useful for policy makers, who have to decide how to allocate public funds. Moreover, it is of interest to private investors operating along the supply chain of FCEB technology components, which is still characterized by fragility, limited capacity to ramp up production or expand spare parts inventory, which currently translates, according to reference [3], into long FCEBs manufacturing times and the slow development of 'package solutions' for hydrogen refueling infrastructure.

The paper is structured in the following sections. In Section 2, the TCO methodology is briefly explained. Section 3 explains the methodology used for the systematic literature review. Section 4 presents and compares the TCO estimates presented in the literature, distinguishing by year and geographical area. Section 5 presents and comments on the data used in the studies. Section 6 concludes the paper by discussing the main findings, highlighting the aspects that have not yet been sufficiently studied and the critical areas in the application of the TCO methodology to FCEBs.

2. The Methodology of the Total Cost of Ownership

Total cost of ownership (TCO) analysis is commonly used to evaluate the cumulative expenses associated with an asset over its entire life span. TCO analysis includes all current and future monetary costs related to purchasing, owning, operating, and eventually disposing of a vehicle. TCO has been recognized as a crucial decision-making model for assessing the feasibility of investments [4,5]. TCO framework has been deployed to evaluate the economic competitiveness of diesel and hydrogen-fueled buses. TCO model is used to quantify all the costs experienced during the entire life cycle of owning and operating the diesel and hydrogen-powered buses. Given that these costs arise at different times, it is essential to apply an appropriate discounting method to accurately assess both costs and revenues.

In the context of bus investments, the literature typically identifies two major types of costs: capital expenditures (CAPEX) and variable operating expenses (OPEX). The fixed capital cost is primarily determined by the purchase price of the bus, which is usually paid at the time of acquisition, and the cost of establishing the necessary infrastructure [6]. When considering the acquisition cost of a hydrogen bus, it is important to account for any subsidies, sales tax or value-added tax (VAT) incurred during the purchase. Subsidies and taxation policies vary significantly across different regions, making it challenging to appropriately calculate the overall cost of hydrogen-powered buses. Despite their potential relevant role in determining the economic competitiveness of hydrogen fueled buses, none of the previous papers has accounted for these aspects. Registration fees also constitute a significant portion of CAPEX. Significant uncertainty exists concerning future trends in hydrogen pricing infrastructure.

Operating expenses (OPEX), on the other hand, encompass cumulative operational costs, including maintenance, fuel and insurance premiums. For hydrogen-powered buses, operational costs can be significantly higher due to extraordinary maintenance and replacement expenses, such as the degradation and replacement of components like fuel cells and batteries [7,8]. Regarding the operational costs of hydrogen buses, fuel expenses are notably variable and difficult to predict. These costs depend on several key factors, such as fuel efficiency and the production cost of hydrogen fuel. Hydrogen can be produced through various methods, categorized by different colors: grey, blue, and green hydrogen are the most common [9]. Among these, green hydrogen is currently the most expensive that is attributed by the higher cost of electricity. Manufacturers typically declare the average fuel consumption of a bus, but substantial discrepancies can occur between proposed and actual fuel consumption due to factors such as total load, driving style, and traffic conditions. Consequently, this variability contributes to uncertain fuel pricing. Over time, fluctuations in diesel prices, also due to disincentivizing tax policies, could influence the relative competitiveness of hydrogen-powered buses.

This study also considers the residual value, such as the revenue generated from the resale of the bus. Accurately determining the residual value of hydrogen buses is highly uncertain due to the fact that this market is not yet mature, resulting in a lack of available data.

In order to directly investigate the economic performance of hydrogen-powered buses, using diesel-fueled buses as a baseline scenario for comparative purposes, it is useful to express the TCO value in EUR/km.

3. Systematic Literature Review

In the pursuit of understanding the economic competitiveness of hydrogen buses we initiated a systematic literature review following the PRISMA guidelines (Figure 1) [10,11]. This preliminary overview was followed by a narrative examination of a curated selection of papers and reports. Our approach involved identifying relevant academic literature, including papers, articles, proceedings, and reviews. We conducted targeted string searches within the Scopus and WOS databases, without imposing temporal restrictions. This analysis resulted in 521 references. Refining by subject area (economic, social, environmental and energy related sciences) and considering only papers in English, we selected 283 papers. Only 11 papers reported TCO specific keywords. Table 1 presents the keywords selected for querying Scopus and WOS databases to sound out papers title, abstract and keywords published between 1975 and July 2024.

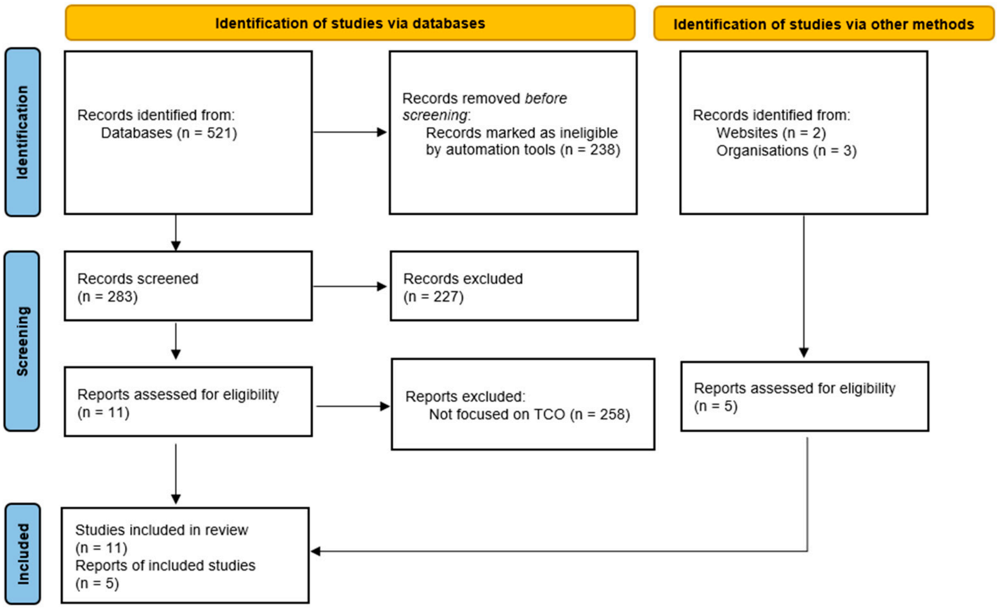

Figure 1. PRISMA 2020 flow diagram [10,11].

Table 1. Keywords for queries.

Preliminary keywords	Bus* AND fuel AND cell AND hydrogen AND cost
Final keywords	Bus* AND fuel AND cell AND hydrogen AND cost AND TCO
Period	1975 and July 2024

To enrich our findings, we integrated data from market reports, European project reports, International Energy agencies reports and technical papers. Furthermore, we employed a funnel search strategy, meticulously analyzing a subset of 16 scientific and technical papers, market reports and analysis [12,13].

A qualitative narrative review was then conducted on this subset of papers focused on the TCO analysis. Papers without data to support TCO, as well as those with aggregated results that did not allow for isolating bus-specific data for TCO analysis, were excluded [14]. Documents and reports from the European Commission and International hydrogen associations were included in the review. Data compilation and extraction were then performed to organize the information.

A bibliometric analysis was conducted on papers obtained by refining search keywords to observe research trends over the years. From 1992 to 2003, the number of studies was limited and infrequent, with a peak in 2007 (Figure 2). However, starting from 2020, there has been a noticeable increase in publications [15].

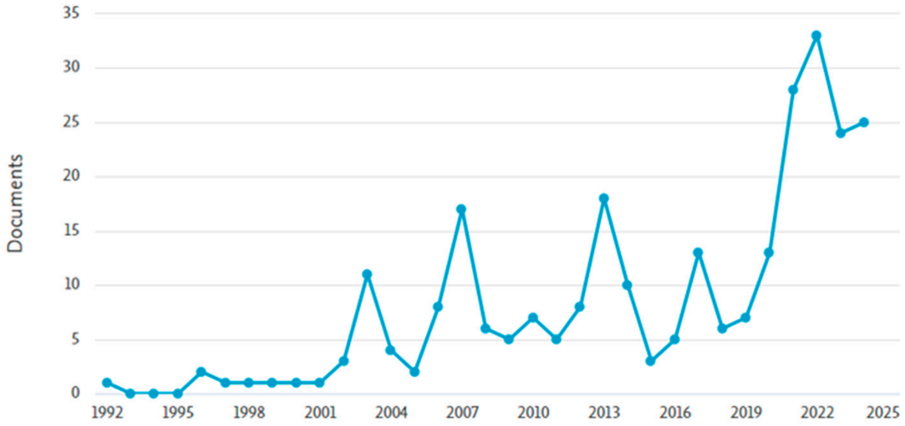

Figure 2. Distribution of articles by year.

The analysis by subject area clearly highlights that the research primarily focuses on technical fields: Energy sector (225 papers—38.9%), Engineering (110 papers—19%), Environmental science (64 papers—11%), as Business management, social science, and economics collectively represent only 8% of the publications.

Figure 3 shows that most prolific authors hail from the USA, with 63 publications. China follows closely with 37, while Germany, the United Kingdom, and Italy complete the top five with 30, 25, and 20 papers, respectively. Analyzing documents by affiliation reveals that the Beijing Institute of Technology and Tsinghua University in China, along with the Argonne National Laboratory in the USA, dominate the ranking.

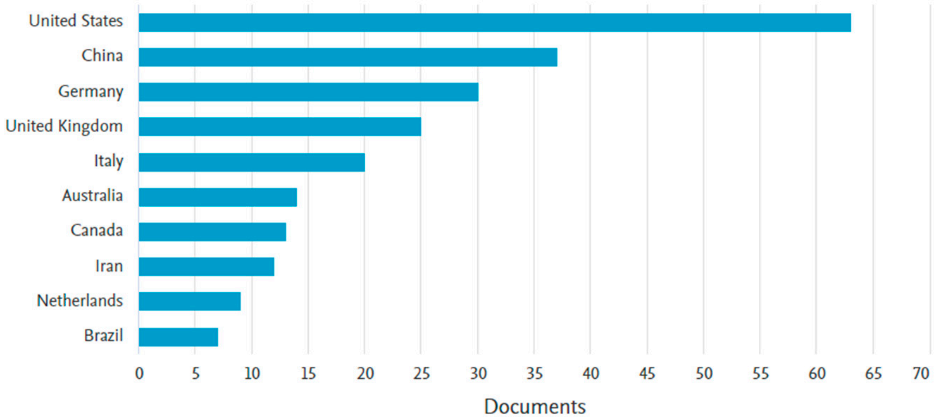

Figure 3. Geographical distribution of scientific studies.

VOS viewer (version 1.6.20) was employed to visualize thematic groupings of the most significant research areas within the investigated domain [13]. By identifying frequently co-occurring terms in abstracts (with a minimum threshold of ten occurrences), VOS viewer identifies clusters of related documents. These clusters represent thematic groups, providing insights into the major themes in the research field. Figure 4 displays the terms/words co-occurrences networks grouped in main 3 clusters. The research in this area adopts a distinctly technical approach. The red cluster emphasizes hydrogen production, electrolysis, and the analysis of hydrogen generation from renewable sources, with a focus on minimizing CO_2 emissions. Simulations and sensitivity analyses play a crucial role within this cluster. The blue cluster centres around storage technologies, fuel cells, and optimizing hydrogen consumption efficiency. Lastly, the green cluster reflects a recent surge of interest in economic analysis. This trend is further supported by bibliometric data and initial studies on the TCO for bus fleets. These studies compare the costs and performance of hydrogen buses against the benchmark, typically represented by diesel buses.

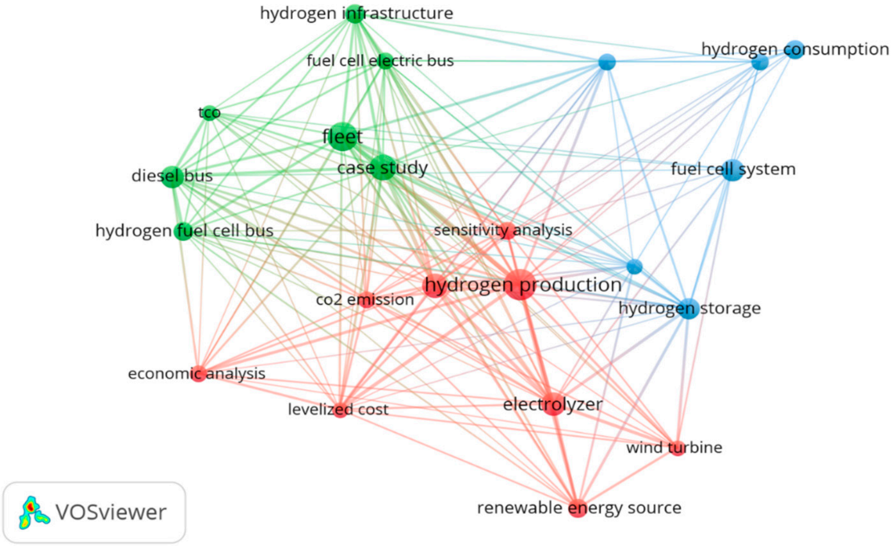

Figure 4. VOS viewer terms co-occurrences.

4. Data

This section illustrates and discusses the data and assumptions used by the various author to estimate the TCO. The focus is on the acquisition costs, hydrogen fuel costs, hydrogen pathways, fuel efficiency, maintenance costs and infrastructure costs.

4.1. Acquisition Costs

Bus acquisition cost is a critical parameter in determining the overall TCO of hydrogen buses. The acquisition cost of hydrogen buses is substantially higher compared to diesel buses due to niche market penetration, as Table 2 indicates.

On average, hydrogen-powered buses are 126% more expensive than diesel buses. It is worth mentioning that to execute this analysis, the authors eliminated one outlier for the acquisition cost of hydrogen buses estimated by reference [9]. The study determined a purchasing cost of $1,300,000 USD for a single bus, which was inconsistent with figures proposed by other studies.

Initially, authors have relied on a bottom-up approach to determine the acquisition cost of hydrogen buses [1,2,8,16]. This approach involves identifying and estimating the monetary value of specific components and summing them to calculate the total purchasing cost of a bus. Previous studies have hypothesized different pricing mechanisms for components, resulting in variability in overall acquisition costs across studies.

The highest cost difference was observed between 2015–2017, when hydrogen buses were more than 200% more expensive than conventional diesel ones. Studies conducted by references [17,18], for example, found consistent ratios for 2016, indicating that hydrogen buses would be 2.6 times more expensive. Reference [16] estimated that hydrogen buses were 2.51 times more expensive in 2023, with this gap shrinking to 1.51 by 2030, indicating approximately a 40% decrease. By 2030, the average ratio of acquisition cost between hydrogen and diesel buses is estimated to be 1.74, with hydrogen buses being 70% more expensive than diesel buses.

Table 2. Acquisition cost of hydrogen- and diesel-powered buses.

Authors	**Year of Reference**	**Acquisition Cost HB (EUR)**	**Acquisition Cost DB (EUR)**	**Acquisition Cost HB/ Acquisition Cost DB**
Fischer & Zenith (2020)	2015	715,000	232,000	3.08
Ally & Pryor (2016)	2016	815,789	309,208	2.64
Kolodziesjski et al. (2022)	2016	926,918	347,594	2.67
Madden & Boyd (2017)	2017	666,000	170,894	3.90
Deloitte (2020)	2019	603,506	257,768	2.82
Madden & Boyd (2017)	2020	500,000	170,894	2.93
Fischer & Zenith (2020)	2020	585,000	233,000	2.51
Kim et al. (2021)	2020	430,000	250,000	1.72
Migliarese Caputi et al. (2022)	2020	625,000	250,000	2.50
Sadik-Zada et al. (2023)	2021	625,000	260,000	2.40
Malek et al. (2021)	2021	280,000	262,000	1.07
Borghetti et al. (2024)	2022	670,000	262,000	2.56
Di Vece et al. (2022)	2023	550,000	219,240	2.51
Sadik-Zada et al. (2023)	2025	472,500	260,000	1.82
Madden & Boyd (2017)	2025	347,766	170,894	2.03
Borghetti et al. (2024)	2025	480,000	262,000	1.83
Fischer & Zenith (2020)	2025	535,000	238,000	2.25
Madden & Boyd (2017)	2030	339,766	170,894	1.99
Borghetti et al. (2024)	2030	380,000	262,000	1.45
Di Vece et al. (2022)	2030	330,000	219,240	1.51
Fischer & Zenith (2020)	2030	505,000	244,000	2.07
Kim et al. (2021)	2030	360,000	250,000	1.44
Sadik-Zada et al. (2023)	2035	320,000	260,000	1.23
Global Average		**505,939**	**231,882**	**2.26**

A decrease in purchasing cost of 30% can be observed from 2020–2030. This downward trend suggests improvements in cost efficiency due to the maturity of technology and the reducing cost of fuel cell systems and hydrogen tanks [8] and to technological advancements and optimization in production chains through economies of scale. The niche market segmentation of hydrogen buses makes their purchasing cost substantially higher than that of diesel buses [7]. This decreasing trend in acquisition cost is also supported by reference [19], which highlighted that the purchase price of hydrogen buses would continue to fall until 2035, with capital costs expected to remain 20% higher than those of diesel buses.

It is noteworthy that most of the studies have been conducted in European countries. There are few studies concerning China. They indicate that hydrogen-powered buses are nearly 300% more expensive than diesel buses. No studies have been identified that take into account the acquisition cost analysis of hydrogen buses in India.

4.2. Hydrogen Fuel Costs

In Table 3, we have reported the price of hydrogen fuel assumed by different authors in comparison with diesel fuel cost while investigating the TCO of hydrogen buses.

Table 3. Estimates for hydrogen fuel and diesel prices until 2035.

Authors	Year of Reference	Hydrogen Price (EUR/kg)	Diesel Price (EUR/L)
Fischer & Zenith (2020)	2015	12.00	
Ally & Pryor (2016)	2016	13.06	1.39
Kolodziesjski et al. (2022)	2016	9.50	
Madden & Boyd (2017)	2017	6.37	0.80
Deloitte (2020)	2019	6.94	0.99
Munoz et al. (2022)	2019	9.70	
Madden & Boyd (2017)	2020	5.43	0.90
Fischer & Zenith (2020)	2020	9.00	
Kim et al. (2021)	2020	13.10	1.24
Migliarese Caputi et al. (2022)	2020	7.24	1.85
Millo et al. (2022)	2020	5.00	1.60
Sadik-Zada et al. (2023)	2021	9.26	0.97
Malek et al. (2021)	2021	6.00	
Borghetti et al. (2024)	2022	12.50	
Sarker & He (2023)	2022	2.40	
Chen & Wang (2023)	2023	4.20	1.03
Di Vece et al. (2022)	2023	5.35	
Sadik-Zada et al. (2023)	2025	7.87	1.17
Madden & Boyd (2017)	2025	4.20	1.00
Borghetti et al. (2024)	2025	10.00	
Fischer & Zenith (2020)	2025	6.00	
Madden & Boyd (2017)	2030	4.00	1.10
Borghetti et al. (2024)	2030	8.00	
Di Vece et al. (2022)	2030	4.00	
Fischer & Zenith (2020)	2030	3.00	
Kim et al. (2021)	2030	7.60	1.37
Sadik-Zada et al. (2023)	2035	5.09	1.56
Global Average		**6.68**	**1.17**

The price of hydrogen approximately is assumed to vary between 6 and 10 EUR/kg with few exceptions. Several authors have also predicted the future price trends, which portrays that until 2030 the price of hydrogen will fall to 3–4 EUR/kg. This downward trend in hydrogen price will be a major breakdown in the TCO. According to reference [19], the scaling of green hydrogen will result in a 17% reduction in the TCO of hydrogen buses compared to that of diesel ones by 2035. Most of the authors assumed maximum and minimum values (best and worst scenario) for performing TCO analysis while some incorporated an average value [16].

4.3. Hydrogen Pathways

The process used to create hydrogen is a significant factor influencing its pricing. It is crucial to distinguish between TCO analyses based on different hydrogen types and production pathways.

As shown in Table 4, three studies ([1,6,9]) estimated TCO using various hydrogen types. All studies found that grey hydrogen without carbon capture is the cheapest. However, hydrogen buses in these studies were not economically competitive with diesel buses in their current analyses. Reference [16] proposed the utilization of photovoltaics as the most economically feasible solution for developing green hydrogen. On the other hand, reference [9] determined that in the United States, hydrogen sourced from on-site Steam Methane Reforming (SMR) without carbon capture has the lowest TCO compared to on-site SMR with carbon capture and on-site electrolysers. This indicates that substantial investment is required to develop cost-effective production of green hydrogen. As far as hydrogen production pathways are concerned, no current technology allows hydrogen-powered buses to be competitive with diesel buses. Ongoing advancements in hydrogen production methods and reductions in associated costs may enhance the economic viability of hydrogen buses in the future.

Table 4. Average price of hydrogen and diesel with alternative technologies.

Authors/Pathways	Year of Estimate	Hydrogen Price (EUR/kg)	Diesel Price (EUR/l)
Madden & Boyd (2017)	2023	5.00	0.95
Alkaline Electrolysis	2023	5.73	0.95
Ploymer Electrolyte Membrane	2023	5.95	0.95
SMR	2023	3.33	0.95
Migliarese Caputi et al. (2022)	2020	7.24	1.85
Electrolysis (through FER)	2020	9.20	1.85
Electrolysis (through Grid)	2020	7.60	1.85
SMR with CCS	2020	4.91	1.85
Chen & Wang (2023)	2026	3.27	1.05
Blue	2023	3.80	1.03
Blue	2028	1.94	1.07
Grey	2023	1.93	1.03
Grey	2028	1.36	1.07
Green	2026	5.30	1.05

Reference [6] reported different prices of hydrogen via Steam Methane Reforming (SMR) with Carbon Storage and Capture (CSS) (4.91 EUR/kg), electrolysis from grid energy (7.60 EUR/kg), and electrolysis from FER (green) (9.2 EUR/kg) energy in the case of Italy. However, the current prices of hydrogen vary geographically throughout the EU, for instance, 7–9 EUR/kg in Germany [19], 8–9 EUR/kg in Poland [18] and the highest being 8–12 EUR/kg in Italy [20].

4.4. Fuel Efficiency

Fuel efficiency is a critical TCO determinant. The main assumptions are reported in Table 5.

These estimates are primarily based on simulation models developed by authors rather on certified values from the manufacturers [2,18]. Most of the authors mentioned fuel efficiency in kg/100 km or kg/km. The data portrays significant variations in fuel efficiency which is primarily due to the size of hydrogen bus. Majority of the authors mentioned 12 m [6] as the size of bus, while other considered 18 m bus size [2] for TCO calculations. Certain estimates highlight potential fuel efficiency improvements of 25–40% from 2020 to 2035 [1,16,20]. However, traffic delays and congestions may increase the operating cost of hydrogen buses in urban areas. From the technical point, geographic location, operating time and stops per distance are crucial determinants of fuel efficiency that suffer diesel buses more than electric and hydrogen buses because of regenerative braking systems [17]. Though less importance is given to these determinants due to lack of real-time data.

Table 5. Fuel efficiency estimates from 2015–2035.

Authors	Year of Reference	Fuel Efficiency (kg/100 km)
Fischer & Zenith (2020)	2015	9.50
Ally & Pryor (2016)	2016	10.00
Kolodziejski et al. (2022)	2016	9.00
Madden & Boyd (2017)	2017	8.00
Madden & Boyd (2017)	2020	7.50
Fischer & Zenith (2020)	2020	9.50
Kim et al. (2021)	2020	8.00
Migliarese Caputi et al. (2022)	2020	8.00
Sadik-Zada et al. (2023)	2021	8.00
Malek et al. (2021)	2021	9.00
Borghetti et al. (2024)	2022	11.00
Di Vece et al. (2022)	2023	6.55
Sadik-Zada et al. (2023)	2025	8.00
Madden & Boyd (2017)	2025	6.50
Borghetti et al.	2025	10.00
Fischer & Zenith (2020)	2025	9.50
Madden & Boyd (2017)	2030	6.50
Borghetti et al. (2024)	2030	9.00
Di Vece et al. (2022)	2030	6.55
Fischer & Zenith (2020)	2030	9.50
Kim et al. (2021)	2030	8.00
Sadik-Zada et al. (2023)	2035	8.00
Global Average		**7.99**

4.5. Maintenance Costs

Maintenance costs are categorized under operational costs in TCO whose estimates are presented below in Table 6.

Table 6. Maintenance cost estimates until 2024.

Authors	Year of Reference	Maintenance and Wear Costs HB (EUR/km)	Maintenance and Wear Costs DB (EUR/km)
Ally & Pryor (2016)	2016	0.62	0.17
Madden & Boyd (2017)	2017	0.42	0.15
Fischer & Zenith (2020	2020	0.40	0.28
Deloitte (2020)	2020	1.10	0.66
Kim et al. (2021)	2021	0.11	0.25
Malek et al. (2021)	2021	0.07	
Di Vece et al. (2022)	2022	0.33	0.32
Kolodziejski et al. (2022)	2022		
Migliarese Caputi et al. (2022)	2022	0.42	0.30
Sadik-Zada et al. (2023)	2023	0.50	0.33
Borghetti et al. (2024)	2023	0.33	0.19
Pettinau et al. (2024)	2024	0.20	0.27
Global Average		**0.45**	**0.31**

The average maintenance cost of hydrogen buses is currently 0.45 EUR/km, which is higher than the 0.31 EUR/km for diesel buses. However, the authors hypothesize that the maintenance cost of hydrogen buses will decrease over time, potentially reaching cost parity with diesel buses by 2025 and beyond. This anticipated trend is attributed to technological advancements and the decreasing costs of batteries and hydrogen fuel [16]. Given the uncertainties related to maintenance costs, the authors have determined the maintenance cost only for the current period.

The majority of these costs are estimated by pilot testing of certain projects or forecasted due to absence of real time data. Data trends shows that 50 to 60 percent of maintenance costs can be reduced over the period of 2020–2035 ([1,2]) due to technological advancements. These costs differ vigorously because of multiple factors including the number of buses of the specific type being discussed, the manufacturer's capability to offer professional on-site assistance, degree of commercialization and production quantities.

4.6. Infrastructural Costs

Some European cities are gradually converting to entirely hydrogen-powered fleets. These are long-term investments and infrastructure for the manufacturing and refueling of hydrogen must be built in addition to the hydrogen vehicles. Hydrogen tanks and stacks of fuel cells can now power energy-efficient urban buses. Rapid hydrogen refueling is an exceptional advantage of hydrogen technology over using rapid DC chargers to power vehicle traction batteries with an estimated time of 10 to 15 min for refueling 35–40 kg [2]. Since the majority of TCO studies assume that infrastructure costs are covered by the price of hydrogen paid at the pump, transport companies are not required to pay for any infrastructure. Infrastructure costs are assumed as 0.21 to 0.17 EUR/km [2] and 249,511 to 212,997 EUR/station [20] until 2030.

Additionally, the infrastructure for hydrogen vehicle refueling at 350 and 700 bar is developing [20]. The spread of hydrogen propulsion systems in both passenger cars and buses is encouraged by these favorable circumstances. From the technical-economic perspective, different studies consider hydrogen production pathways, storage levels (high pressure or liquid) and its distribution at levelized cost but lacks its focus on commercial production and distribution channels.

5. TCO Estimates

This section illustrates the TCO estimates presented in the literature. They are discussed by the year to which the estimate refers to, and the country of application.

5.1. Year Wise Estimate

The TCO analysis presented in this study enhances the accuracy of assessing the economic competitiveness of hydrogen-powered buses by pooling data obtained from the literature. Table 7 provides TCO estimates for hydrogen buses, referencing the findings from previous studies up to the year 2035.

Table 7 illustrates the clear decreasing trend between the average TCO ratio of hydrogen to diesel buses from 2015 to 2035. Currently, the average TCO for hydrogen buses is 2.00 EUR/km, compared to 1.44 EUR/km for diesel buses, indicating that hydrogen-powered buses are approximately 40% more expensive than their diesel counterparts.

Comparative analysis suggests that hydrogen-powered buses will become only 25% more expensive than diesel-powered buses starting from 2025 onwards. According to reference [5], this gradual reduction in TCO is primarily due to the declining cost of electricity to produce green hydrogen and the decreasing investment costs related to hydrogen technologies, which strongly supports the increased market penetration of hydrogen buses.

As illustrated in Table 7, the TCO for hydrogen buses decreases from 4.12 EUR/km in 2015 to 1.41 EUR/km in 2035. This noticeable reduction in the TCO ratio over time suggests improvements in the overall cost efficiency of hydrogen buses as technology and associated infrastructure evolve. Such a decreasing trend is encouraging, as it suggests that potential cost parity for hydrogen buses could be achieved as early as 2030 [16] or by the beginning of 2035 [19].

Table 7. Current and future TCO estimates.

Year of Reference/Authors	**TCO HB (EUR/km)**	**TCO DB (EUR/km)**	**TCO HB/ TCO DB**
2015	**4.12**	**2.30**	**1.79**
Fischer & Zenith (2020)	4.12	2.30	1.79
2016	**4.89**	**1.45**	**2.39**
Ally & Pryor (2016)	4.89	1.45	3.37
Kolodziejski et al. (2022)			1.41
2017			**1.58**
Madden & Boyd (2017)			1.58
2019	**2.08**	**1.07**	**1.85**
Deloitte (2020)	1.81	0.96	1.74
Munoz et al. (2022)	2.89	1.40	2.07
2020	**1.70**	**1.27**	**1.31**
Madden & Boyd (2017)			1.30
Fischer & Zenith (2020)	3.65	2.50	1.46
Kim et al. (2021)	1.99	1.17	1.70
Migliarese Caputi et al. (2022)	1.39	1.07	1.30
Millo et al. (2022)	1.26	1.10	1.15
2021	**1.70**	**1.17**	**1.60**
Sadik-Zada et al. (2023)	1.88	1.17	1.60
Malek et al. (2021)	1.35		
2022	**2.15**	**1.10**	**1.95**
Borghetti et al. (2023) *	2.15	1.10	1.95
2023	**2.59**	**2.04**	**1.36**
Chen et al. (2023) **			1.46
Di Vece et al. (2022)	1.57	1.30	1.21
Heimes et al. (2023)	4.64	3.53	1.31
2025	**1.92**	**1.47**	**1.25**
Sadik-Zada et al. (2023)	1.63	1.28	1.28
Madden & Boyd (2017)			1.10
Borghetti et al. (2023) *	1.79	1.10	1.63
Fischer & Zenith (2020)	3.46	2.80	1.24
2030	**1.81**	**1.61**	**1.12**
Madden & Boyd (2017)			1.10
Borghetti et al. (2023) *	1.75	1.10	1.59
Di Vece et al. (2022)	1.20	1.36	0.88
Fischer & Zenith (2020)	3.50	3.00	1.17
Kim et al. (2021)	1.41	1.23	1.15
2035	**1.41**	**1.46**	**0.97**
Sadik-Zada et al. (2023)	1.41	1.46	0.97
Sarker & He (2023)	1.26		
Global Average	**2.00**	**1.44**	**1.38**

Note: *: Borghetti et al. (2023) absolute values of diesel were obtained from Migliarese Caputi et al. (2022) because both studies were conducted in Italy. **: Chen & Wang (2024) average TCO values were derived from the graph.

However, reference [20] remains pessimistic in their TCO analysis, suggesting that even in 2030, hydrogen buses would be approximately 60% more expensive than their diesel counterparts if the fuel-cell replacement costs are included. It is interesting to highlight that diesel buses are expected to maintain their economic advantage until 2025–2030. Beyond this period, existing analyses predict that alternative technologies, such as hydrogen buses, will have comparable TCO. Reference [18] also estimated comparable results, identifying that the TCO of hydrogen-powered buses will be economically competitive with conventional alternatives by 2024.

5.2. Country Estimates

In TCO estimation, regional factors play a significant role in determining the overall cost competitiveness of buses. Table 8 reports the findings of the analyzed studies, grouped by the geographical area of the country where the study was conducted. From a geographical perspective, countries vary in their abundance of natural resources, size, and mechanisms for direct and indirect taxation. These differences translate into unique hydrogen pricing determinations, which are reflected in country-specific TCO metrics and ultimately impact the economic competitiveness of hydrogen buses.

Table 8. TCO values for different countries and years.

Country	Year of Reference	TCO HB (EUR/km)	TCO DB (EUR/km)	TCO HB/ TCO DB
Argentina	2019	**2.89**	**1.40**	**2.07**
Australia	2016	**4.89**	**1.45**	**3.37**
China	2019	**1.58**	**0.66**	**2.39**
Europe		**2.14**	**1.69**	**1.25**
	2015	4.12	2.30	1.79
	2017			1.58
	2019	1.69	1.10	1.53
	2020	1.86	1.45	1.26
	2023	1.57	1.30	1.21
	2025	3.46	2.80	1.13
	2030	1.96	1.90	1.04
Germany		**1.86**	**1.47**	**1.28**
	2020	1.99	1.17	1.70
	2021	1.88	1.17	1.60
	2023	4.64	3.53	1.31
	2025	1.63	1.28	1.28
	2030	1.41	1.23	1.15
	2035	1.41	1.46	0.97
India	2022	**1.26**		
Italy		**1.64**	**1.09**	**1.51**
	2020	1.39	1.07	1.30
	2022	2.15	1.10	1.95
	2025	1.79	1.10	1.63
	2030	1.75	1.10	1.59
Poland		**1.35**		**1.41**
	2016			1.41
	2021	1.35		
USA		**2.17**	**1.11**	**1.55**
	2019	2.17	1.11	1.95
	2023			1.46
Global Average		**2.00**	**1.44**	**1.38**

Regionally, the European Union is at the forefront of advancing the carbon neutrality of commercial vehicles by considering hydrogen-powered buses. Table 8 highlights the economic competitiveness of hydrogen-powered buses in terms of current and probabilistic TCO. The lack of competitiveness with respect to their diesel counterparts is particularly pronounced in Australia and China, mainly due to the high production cost of hydrogen.

Conversely, Poland demonstrates the greatest economic competitiveness among all countries, primarily due to lower electricity production costs that subsequently reduce hydrogen production costs, underscoring the critical role of regional factors in TCO analysis [18]. Germany shows a declining trend in the ratio between TCO of hydrogen and diesel buses, attributed to decreasing electricity prices in the country since 2019 [5]. Reference [16] emphasizes that geographical regions with minimal green hydrogen production costs should be prioritized in future for economically competitive production of green hydrogen.

Compared to European countries, the academic community in the United States has largely overlooked the potential TCO of hydrogen-powered commercial buses. Reference [1] estimated that in 2019, hydrogen powered buses were 95% more expensive than their diesel counterparts in United States. However, recent analyses indicate that this cost disparity has decreased to 46% in 2023. Additionally, there are very few studies from Asian countries evaluating the economic viability of hydrogen buses. For instance, in 2019, hydrogen powered buses were nearly 2.39 times more expensive in China than conventional buses. Such high ratio is mainly attributed to the limited infrastructure and high production cost of hydrogen in the region. Considering Asian countries, an estimate indicates that the average TCO of a hydrogen-powered bus in India will be 1.65 EUR/km by 2030 [21]. Such optimistic TCO estimation is mainly attributed to mass market penetration of blue hydrogen.

6. Conclusions and Recommendations

In this paper we presented a comprehensive overview of economic and technical papers and market reports analyzing the TCO methodology applied to the FCEBs. Our review encompasses the methodology used, the considered variables, estimations, and the resulting outcomes. While there are relatively few papers focusing on economic and TCO methodology beyond the environment aspects, the selected studies cover multiple continents, excluding Africa. The geographic coverage of the papers indicates that the transition to less polluting vehicles for urban and suburban bus fleets is a globally recognized and prioritized issue addressed in policy agendas. While most papers are academic and technical, global consulting firms, European agencies, and U.S. organizations have engaged in detailed economic analyses and market forecasts to inform and address industry investments and government policies [1,22]. The papers selected for our analysis provide initial insights to public and private decision-makers regarding the competitiveness of this propulsion method compared to the currently employed alternatives.

The TCO methodology proves particularly effective for urban and suburban public transport fleet managers. Their task is to minimize the environmental impact of public transport, as required by transition energy policies, while also reducing costs (a challenging aspect, especially when quantifying the impact of new technologies entering the market). Simultaneously, they aim to maintain a high standard of service quality for citizens. The papers we analyzed explore scenarios and conduct sensitivity analyses to assess the technical and economic feasibility of replacing current diesel or compressed natural gas (CNG) fleets with hydrogen-powered buses [5–7,16,19,23].

The prevailing literature on TCO estimation for hydrogen buses has garnered considerable attention within the European Union's academic community. Most of the recent research on hydrogen buses focus on developed nations. To grasp the full worldwide impact of this technology, we must broaden our geographic scope to encompass African, Asian, and developing nations. However, there is a notable lack of evidence regarding TCO analyses for hydrogen buses in the United States and Asian countries. This paucity of empirical data has limited the geographical scope of such comparative studies, with a predominant focus on Germany, Italy, and Poland. Hence, future research needs to expand the geographical coverage by conducting comparative analyses and meta-analyses to update and refine TCO estimates across regions. Having a wider view will assist in recognizing distinct obstacles and possibilities, promoting a more encompassing and inclusive strategy towards sustainable transportation.

Although FCEBs are gradually playing a role in some countries/cities, most data on hydrogen buses comes from modelling and simulations, with about 90 percent of studies relying on these methods. These approaches cannot fully capture the complexities of real-world conditions. To obtain precise estimates and a true understanding of hydrogen bus performance, we need more real-world data. This will provide insights that are crucial for making informed decisions and advancing the technology effectively.

The TCO analysis in this study reveals that prevailing literature predominantly employed bottom-up simulation models for their estimates. This approach, supported by varying assumptions across different reviewed studies, resulted in significant variability in the overall TCO estimates. The variability in TCO estimations can also be attributed to regional factors that substantially influence the two most critical determinants of TCO analysis: the acquisition cost of the bus and the cost of hydrogen fuel [9,16]. In comparative assessment studies, the quality and quantity of data play a vivid role in providing accurate estimates. Among the analyzed studies, grey literature was found to be richer in information than journal articles.

The acquisition cost of the vehicle is arguably one of the important parameters in determining the economic viability of hydrogen buses. Hydrogen buses have a high entry cost compared to diesel buses due to the additional drivetrain components and cost premiums associated with their operations. Acquisition costs are also subject to several uncertainties given the niche market penetration and geographical context. Furthermore, a lack of comparison with actual market data was observed, as the prevailing literature mostly relied on bottom-up simulations for estimating the acquisition cost of hydrogen buses.

Currently, from an acquisition cost perspective, hydrogen buses are not economically competitive compared to their diesel counterparts. This lack of competitiveness is even more pronounced in the United States and China. However, TCO literature delineates a decreasing trend in the acquisition cost of hydrogen buses and their potential competitiveness within the next decade, attributed to technological maturity and the decreasing cost of fuel cell batteries. In this context, a key question is to what extent the operating cost of hydrogen buses would offset the higher CAPEX to achieve TCO parity with baseline diesel-powered buses. From a monetary perspective, the acquisition cost competitiveness of hydrogen buses greatly depends on the cost of fuel cell batteries. Future literature can significantly enhance the modelling and analysis of TCO estimates by incorporating the subsidies required to achieve cost parity for the acquisition of hydrogen buses.

A plethora of authors have proposed that the decreasing cost of fuel cell batteries will ultimately reduce the acquisition and maintenance costs of hydrogen buses, attributing to a 15% reduction in value creation. Mass penetration of fuel cell batteries can substantially encourage economies of scale for hydrogen bus production. The efficiency of fuel cell batteries is contingent on annual mileage, decreasing by 15–20% after 200,000–350,000 km. An annual production of 75,000 fuel cell batteries would represent mass market penetration, lowering the cost of fuel cells to 55 EUR/kW from the niche market segmentation cost of 280 EUR/kW.

In TCO analysis, the price of hydrogen as a fuel is arguably an important parameter in determining the overall economic competitiveness of hydrogen buses. Quantifying hydrogen fuel prices is complex due to the involvement of various pathways and technologies, each with different energy densities, economic implications, and environmental impacts. Uncertainties regarding fuel prices are significantly evident in the prevailing literature, mainly due to the heterogeneous nature of regional electricity pricing infrastructures. Currently, due to the high pricing infrastructure of hydrogen fuel, diesel buses remain more economically competitive. Potential cost parity could be achieved if the production price of green hydrogen is lowered to between 5 EUR/kg [2] and 3 EUR/kg [6]. However, there is a lack of sufficient evidence in determining the TCO of hydrogen buses when considering centralized versus decentralized hydrogen production. The prevailing literature forecasts significant developments in this area, attributing a clear decreasing trend and projecting competitiveness by 2030. It is of paramount importance to recognize that pricing infrastructure is highly sensitive to the geographical region where the electricity is produced.

Regarding hydrogen pathways, many authors propose the utilization of grey and blue hydrogen given its cost competitiveness compared to green hydrogen, especially for large buses. Further complication arises from the various methods through which hydrogen can be produced whether from fossil fuels or renewable sources, and distributed in different physical states, as highlighted by numerous scholars. This proposal is based on the fact that, in the majority of countries, electricity is not entirely produced from renewable sources. Analysis of the estimates indicates that using grid hydrogen and green hydrogen increases operating costs by 13.51% and 21.50%, respectively, compared to grey hydrogen. However, the lack of economic competitiveness of hydrogen buses is pronounced across all pathways. Potential TCO parity might be achieved by 2035, mainly attributed to the establishment of a value chain for green hydrogen coupled with energy subsidization schemes. It is desirable for future TCO analysis to identify the optimal percentage for subsidies and their overall impact on cost competitiveness. The prevailing literature mainly adopted a straightforward approach by considering the fuel price at the pump, leaving the logistics of fuel outside the equation. Potential opportunities and efficiencies that could be realized through integrated hydrogen production are greatly overlooked. Complex decision-making methods are involved in estimating the logistical operations of fuel. Logistical operations of hydrogen fuel substantially depend on the state and medium of fuel transportation. Future literature can support this transformation by accounting for the complexities involved in centralized versus decentralized hydrogen production.

The existing literature primarily focuses on predicting future advancements in hydrogen infrastructure. The incorporation of infrastructure costs in TCO is still undefined. The prevailing approach in most studies is to presume that the expenses related to infrastructure are encompassed within the price of hydrogen dispensed at refueling stations, thereby exempting transport companies from bearing any infrastructure costs. Furthermore, this perspective fails to recognize the opportunity to evaluate the potential synergies arising from the integration of hydrogen generation and consumption. An inherent benefit of hydrogen-powered vehicles lies in their ability to support fleets of vehicles sharing a common depot.

An important observation to note is that despite the current lack of cost efficiency in hydrogen buses compared to diesel ones, they are expected to become competitive in the coming decade. Substantial uncertainties were reported by the authors regarding TCO estimation for hydrogen buses due to their limited commercial availability. Nevertheless, all reviewed studies consistently expressed optimism about the future potential of hydrogen-powered buses. This optimism is supported by a clear downward trend in the overall TCO for hydrogen buses in this study. Such a gradual reduction in TCO is primarily attributed to the decreasing cost of electricity, the annual increase in diesel fuel prices, technological advancements, and the decreasing cost of batteries and fuel cells. This has the potential to impact decisions regarding investments from both public and private sectors. It is crucial that comprehensive evaluations of TCO in future scenarios are conducted meticulously. This thorough examination plays a vital role in recognizing the specific elements that could make hydrogen buses financially feasible soon.

From a market segmentation perspective, the literature has overlooked the TCO estimation of hydrogen buses of varying sizes. Instead, the reviewed studies mainly relied on a standardized approach, focusing specifically on 12 m buses for urban transportation. The overall economic viability of hydrogen buses appears to be greater for small to mid-sized cities. Conversely, for interurban transportation, hydrogen buses would require large fuel-cell batteries, which could affect their driving range due to the extra weight of the batteries. Instead, hydrogen tanks are proposed as a feasible option due to the lower weight of hydrogen fuel. Given the niche market penetration of hydrogen buses, the public transportation sector and transit agencies are anticipated as early adopters for urban and interurban transportation, respectively. In the commercial heavy-duty transportation sector, TCO plays a decisive role for fleet operators in determining the economic viability of a powertrain technology. The reviewed studies mainly estimated TCO for fleet-wide data of urban transportation, adhering to the dogma that such transportation is largely financed through public funds. A common theme among the analyzed studies is that the majority of TCO estimations were carried out using a case study approach for fleets of buses in urban public transportation, with daily mileage ranging from 200 to 350 km. However, it is desirable for future studies to estimate the economic viability of hydrogen buses for interurban transportation over long distances.

Transitioning to hydrogen-powered buses involves complex cost considerations. Most of the reviewed articles estimated TCO for fleets of buses, reflecting the nature of the market for which the analysis is conducted. A significant fleet size is essential to distribute fixed acquisition costs over more units, thereby reducing the per-unit cost. The economic viability of a fleet of buses is significantly higher than that of a single bus due to shared infrastructure and more efficient maintenance schedules. Prevailing literature advocates for the decisive role of decreasing TCO through mass market penetration to encourage optimization in production chains via economies of scale.

Substantial variability was observed in the statistical figures provided regarding the minimum threshold needed to foster economies of scale for hydrogen-powered buses. It is proposed that by 2025, the cumulative deployment of at least 8000–10,000 hydrogen buses per annum is required to achieve economies of scale. However, if the market penetration of hydrogen buses ranges between 1200 and 2000 buses, the market would still be considered niche for Europe. Evidently, the reviewed empirical studies do not explicitly provide a minimum threshold number to ultimately achieve economies of scale for hydrogen-powered buses. It is important for the academic literature to enhance TCO estimation by establishing a consensus on the minimum threshold required to achieve economies of scale for hydrogen-powered buses in the market.

Comprehensive data on the TCO for hydrogen buses is lacking in various crucial aspects. There is a scarcity of information regarding insurance costs, maintenance costs, and infrastructure costs. Moreover, the data concerning depreciation costs, salvage cost or resale value is constrained. Inadequate coverage of the literature is also observed in terms of operating time, geographical data, labor costs, and road toll taxes. These deficiencies impede a holistic comprehension of the financial ramifications associated with the adoption and utilization of hydrogen buses. It would be desirable for future TCO estimations to clarify the relationship between hydrogen pathways and their correlation with TCO estimation. Similarly, the prevailing literature has widely overlooked the infrastructure costs associated with the deployment of hydrogen buses. Estimating these infrastructure costs would significantly update the TCO estimation of hydrogen buses, acting as a catalyst for mass market penetration and the cost competitiveness of hydrogen fuel.

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