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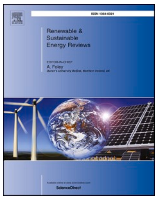

Factors influencing the adoption of zero-emission buses: A review-based framework

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ABSTRACT

Zero-emission buses (ZEBs) currently face the challenge of switching from small-scale implementation to large-scale deployment. This stage is affected by multiple decision-making factors that either hinder or enable the ZEB adoption, also depending on local contexts and stakeholder perspectives. This study develops a holistic framework relating the transition towards ZEB fleets based on an extensive literature review. The review aims at fully capturing the supporting and limiting factors for the bus fleet decarbonisation and organising them in a comprehensive taxonomy and hierarchy. Subsequently, the impact of each of the identified factors was quantitatively analysed. The results show that technological, economic and managerial factors have hampered the large-scale deployment of ZEBs, while social, environmental, and institutional dimensions have stimulated their diffusion. However, more recent studies show that advances in the technological and managerial domains are reducing some drawbacks linked to ZEBs. Finally, the proposed framework is used to identify factors of growing significance that merit further research.

1. Introduction

The transport sector is currently one of the most significant contributors to climate change, playing a pivotal role in aligning urban economics with the global Sustainable Development Goals (SDGs). To address this issue, the transition towards cleaner power supply modes is gathering speed, considering both private vehicles and commercial fleets [1,2]. At present, electric powertrains are the only technology able to nullify harmful emissions from the tailpipe, using the energy provided by an electric battery or a fuel cell (i.e., hydrogen-feed). Although the environmental impact of these technologies (from a life-cycle perspective) depends on electricity and hydrogen generation mix and on the production and disposal of their components [3,4], they are also known as zero-emission vehicles.

In this context, public-funded bus services are ideal for testing the effects of transitioning from the early adoption to the early majority diffusion of these new technologies [5], and crossing the “chasm” to market penetration described by Berkeley et al. [6] for electric vehicles. Indeed, certain characteristics of public transport services make them particularly well-suited to electric powertrains. First, transport providers operate with fixed routes and schedules, centralised depots and shared infrastructures [7], thereby limiting the impact of any drawbacks linked to electric battery range. The high yearly mileage of transit buses brings more leverage to the lower running costs of an electric powertrain compared to fossil fuelled options [8]. In addition, regulated utilities are more subject to public scrutiny [9], and thereby often subject to obligations and direct incentives introduced by national and local governments. In this regard, the high visibility of urban buses may help to raise public awareness of the importance of fighting air pollution, climate change and fossil fuel imports [10]. Finally, zero-emission buses (ZEBs), in addition to directly reducing harmful emissions, may indirectly improve air quality, habitat damage, congestion and noise within cities by influencing a modal shift from single-occupant vehicles to public transport. Indeed, some travel surveys have found a higher willingness to use a bus if it is electric [11,12], even at a higher fare (for people deeply concerned about environmental issues, such as young people) [13]. For these reasons, bus fleet decarbonisation strategically aligns with different SDGs. Notably, the explicit inclusion of public transport expansion in SDG target 11.2 (Affordable and sustainable transport systems) underscores its significance, while ZEBs also directly contribute to SDG 13 (Climate Action) by mitigating greenhouse gas emissions and air pollution.

Accordingly, governments worldwide are boosting public policies to promote ZEB deployment [1]. To such an extent that certain predictions, particularly in urban areas, anticipate a complete shift to electric city

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List of abbreviations

including units and nomenclature

Greenhouse Gas Emissions	GHG
Sustainable Development Goals	SDGs
Zero-emission buses	ZEBs

buses within the current decade [14].

Despite these advantages, the market penetration of ZEBs is not significantly larger than that of private electric vehicles. In the EU in 2021, full electric cars accounted for 9.1% of all new registrations, similar to electric buses, which accounted for 10.1% [15,16]. Worryingly, while diesel cars represent less than 20% of new car registrations, conventional diesel buses still account for more than 60%.

An extensive literature has addressed the consumer preferences for electric vehicles, and the literature presents various reviews of the factors influencing electric vehicle adoption (e.g., Refs. [17–23]). While ZEBs have received less attention overall [24], the number of studies focusing on electric buses has exponentially grown over the last 5 years [7,25,26]. The most frequent topics addressed in the literature with respect to electric buses are operations management (e.g., energy consumption, charging scheduling), cost-benefit analyses, and environmental and social aspects. More recently, the issue of charging infrastructure planning for transport electrification has been analysed by considering both private vehicles and public fleets [27].

In general, several studies have dealt with the decision-making process related to ZEB adoption, which involves public transport authorities, transport operators and other stakeholders of growing importance (e.g., Refs. [28–31]).

Given the burgeoning literature exploring the transition to a cleaner public transport, this research aimed at fully capturing the debate over the barriers to and enablers of ZEB adoption. Building on an extensive and up-to-date review of the literature on alternatively powered buses, it is proposed a holistic framework for mapping and assessing the decision-making factors that influence the large-scale deployment of ZEBs. To this end, the entire transition process is considered without adopting a specific perspective related to one of the multiple actors involved. Indeed, the limiting or enabling effect of each factor may change, depending on stakeholder standpoints and local contexts. This underlines the importance of collaborative governance for bus fleet renewal projects, as already highlighted in the literature [32–36].

This study contributes to the literature in three respects. First, it defines a comprehensive framework that includes all of the decision-making factors identified in the literature as barriers to or enablers of the transition to a ZEB fleet, as well as a taxonomy for scientific research and practitioners approaching the study of bus fleet decarbonisation. Second, it provides a quantitative analysis of the influence direction (hindering or enabling) of each factor, based on a systematic comparison of the case studies presented in the literature. It also investigates the time trend effects of technological and managerial progress on these factors. Finally, it identifies factors of growing significance that merit further research.

The paper is organised as follows: Section 2 summarises the methodology used to collect and analyse the relevant studies; Section 3 describes the ZEB fleet transition framework; Section 4 presents the quantitative results and findings; and Section 5 provides concluding remarks.

2. Method

2.1. Search strategy and study selection

This research is based on an extensive and up-to-date review of the literature on the barriers to and enablers of bus fleet decarbonisation, aimed at identifying and mapping decision-making factors affecting the large-scale development of ZEBs. A literature search was conducted on the Scopus database, using 31 keywords reported in Table 1.

The research queries were based on three main sets of keywords, combined through the Boolean operator AND, namely: the first group related to the bus technology taxonomy, the second focused on decision-making factors (e.g., barriers, motivators, challenges, innovation, etc.), and the third limited the analysis to the bus sector. The search was restricted to article titles and keywords, in order to maintain the strict scope of the study. To ensure that all relevant studies on the barriers to and enablers of the ZEB transition were included in the review, the sample of papers was further expanded by using the snowballing literature review method. This enhanced the validity of the review with reference to backward and forward citations [37]. The most relevant papers were those discussing the ZEB adoption process and those identifying challenges and opportunities for transport operators, public transport agencies, and other stakeholders. While this analysis focused on the bus sector, it also includes major studies dealing with the diffusion of alternative fuel vehicles within industrial fleets (e.g., general heavy-duty vehicles, commercial fleets). It is worth noting that barriers and enablers relating bus fleet decarbonisation were often investigated without any differentiation between power technologies; indeed, many studies referred broadly to alternative fuel powertrains (e.g., Refs. [28,38]). This study focuses on so-called zero-emission buses (i.e., battery electric buses and fuel cell buses), which are able to nullify the pollution produced from the tailpipe (in the tank-to-wheel stage).

The final set of papers included 47 peer-reviewed journal articles, 2 papers published in conference proceedings and 1 book chapter. All papers were published in the period 1997–2022, as the publication search window ended in December 2022.

2.2. Content analysis and data collection

The research was conducted by carrying out a two-step content analysis of the selected articles, as shown in Fig. 1.

First, to identify the decision-making factors and facilitate comparison, each paper was classified according to a grid highlighting the main relevant aspects. In particular, information was gathered regarding the study objectives, methods, geographical location of the case studies, and power technologies under review. A content analysis was conducted using inductive reasoning, as this approach is considered particularly effective for analysing innovation diffusion processes [38].

While this context-sensitive exploration of the influencing factors offers a comprehensive understanding of identified challenges and opportunities in the literature, it suffers the potential for subjectivity in the interpretation of findings. The human-conducted collection of an extensive array of factors, based on the review of numerous case studies, proved to be time-consuming; however, it was essential for ensuring the

Table 1
List of the keywords used in the automatic literature search.

Power technologies	Technology adoption		Bus sector
Zero-emission	Decision-mak*	Trend	Bus
Electric	Factor	Adoption	Transit
Electrification	Barrier	Acceptance	Public transport*
Fuel cell	Deterrent	Criteria	
Hydrogen	Motivator	Transition	
Biogas	Driver	Purchase	
Alternative fuel	Challenge	Procurement	
		Innovation	
Biofuel	Enabler		
Renewable	Opportunity		
Natural gas	Tendency		

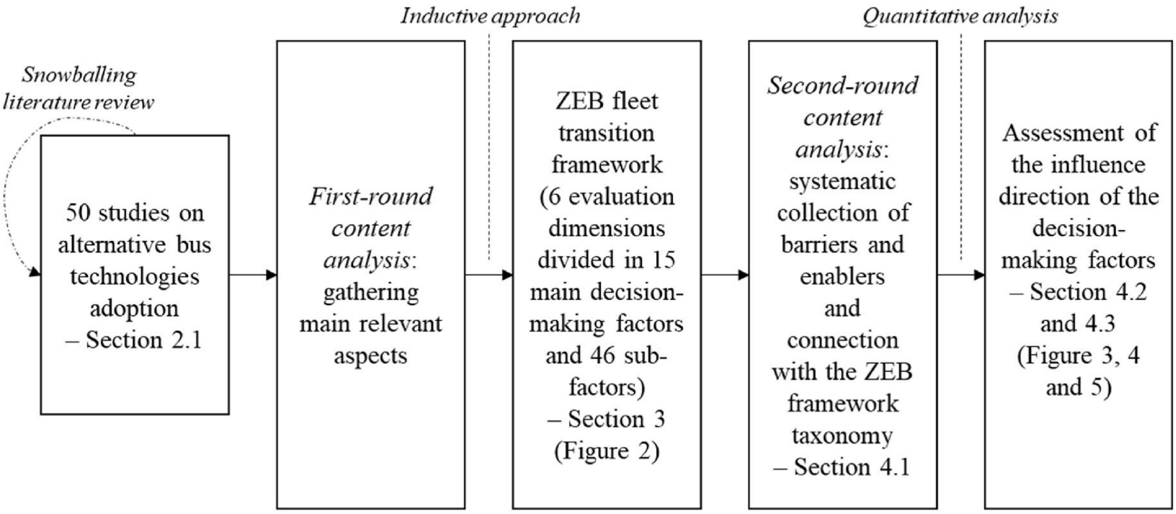

Fig. 1. Content analysis workflow.

identification of decision-making factors grounded in a contextual and critical understanding. The absence of a specific perspective related to any single actor in the framework adds another layer of complexity, as it requires reconciling the varied interests and priorities of multiple stakeholders. Notably, the proposed taxonomy has to recognise that factors may function as both barriers and enablers depending on the stakeholder standpoint and local context. This approach, applied consistently across the entire framework, guarantees its flexibility in addressing different regional and situational nuances. For example, the impact of well-to-wheel emissions of electric buses was found to vary depending on the electricity production methods in a given country [39,40]. From a policy-making perspective, in regions with a high share of renewable energy, this factor acts as an enabler, whereas in contexts relying on fossil energy sources, it serves as a deterrent to ZEBs promotion. Then the framework can be effectively applied to different local contexts by calibrating the influence direction (i.e., hindering or enabling) and the scale of impact of each factor according to peculiar characteristics of the case study.

Second, the identified decision-making factors of the proposed framework were quantitatively analysed. This analysis was based on a deeper second reading of the articles to systematically gather data about deterring and facilitating factors identified in each study. Through this process, it was obtained a dataset of 768 barriers to and enablers of ZEB adoption, with each attached to one or more components of the proposed framework. The built database formed the basis for calculating descriptive statistics on the frequency with which each factor was mentioned in the different case studies, also considering differences linked to the time of publication. In this way, this research provides a detailed overview of how challenges and opportunities associated with the large-scale deployment of ZEBs have been explored in the existing literature.

3. ZEB fleet transition framework

This section introduces the holistic framework that was developed to define the comprehensive taxonomy of the decision-making factors affecting ZEB adoption. The framework displays a hierarchical structure, consistent with other models developed for multi-criteria decision-making in transport and energy sectors [2,41–43].

The first hierarchical level consists of six evaluative dimensions: (i) technological, (ii) economic, (iii) managerial, (iv) social, (v) environmental and (vi) institutional. Four of these are inspired by the prism of sustainability [44], which extends the well-known *three pillars approach* [45] to the institutional sphere. The technological and managerial dimensions relate to technology adoption theories, with respect to innovation and environmental management. In this respect, it can be mentioned some seminal contributions: the *technology, organisation and environment* (TOE) *model* [46], the *unified theory of acceptance and use of technology* (UTAUT) [47] and the *attributes of innovation* identified by Rogers et al. [48]. These models also include non-technical aspects that steer innovation diffusion, which have been extensively investigated with respect to the consumer adoption of electric vehicles (e.g., Refs. [20,49,50]), but much less with respect to the mass-transit sector. Only a few studies have also considered this perspective with respect to alternatively fuelled buses (i.e. [10,28,30]).

The six evaluative dimensions are articulated in 15 decision-making factors, which, in turn, comprise 46 sub-factors that can positively or negatively impact the transition to ZEBs. Fig. 2 displays the hierarchical structure of the ZEB fleet transition framework.

The proposed framework is also interrelated with various Sustainable Development Goals (SDGs), in line with other frameworks focusing on environmental preservation [51]. Firstly, the enhancement of public transport aligns closely with SDG 11 (Sustainable Cities and Communities) by curbing pollution and alleviating congestion, as well as pursuing equity goals related to the level of accessibility and affordability of the transport systems. The identified factors within the environmental dimension seek to measure the contribution of ZEB transition to SDG 13 (Climate Action) by mitigating greenhouse gas emissions and climate change. Notably, the decision-making factor relating the life-cycle assessment of vehicles and infrastructure also considers the importance to ensure responsible consumption and production (SDG 12). The technological and managerial dimensions further align with SDG 9 (Industry, Innovation, and Infrastructure), as various stakeholders are interested in evaluating how cleaner bus services foster innovation in transportation technologies and support the development of sustainable energy supply infrastructures. Finally, the SDG 8 (Decent Work and Economic Growth) is included in the proposed framework through the social dimension, which is gaining increasing relevance also in modern climate action planning [52].

3.1. *Technological dimension*

The first evaluative dimension focuses on the impact of the power technology on the ability to effectively and efficiently provide transit services.

3.1.1. *Technical and operational performance*

Technical and operational performance refers to vehicle

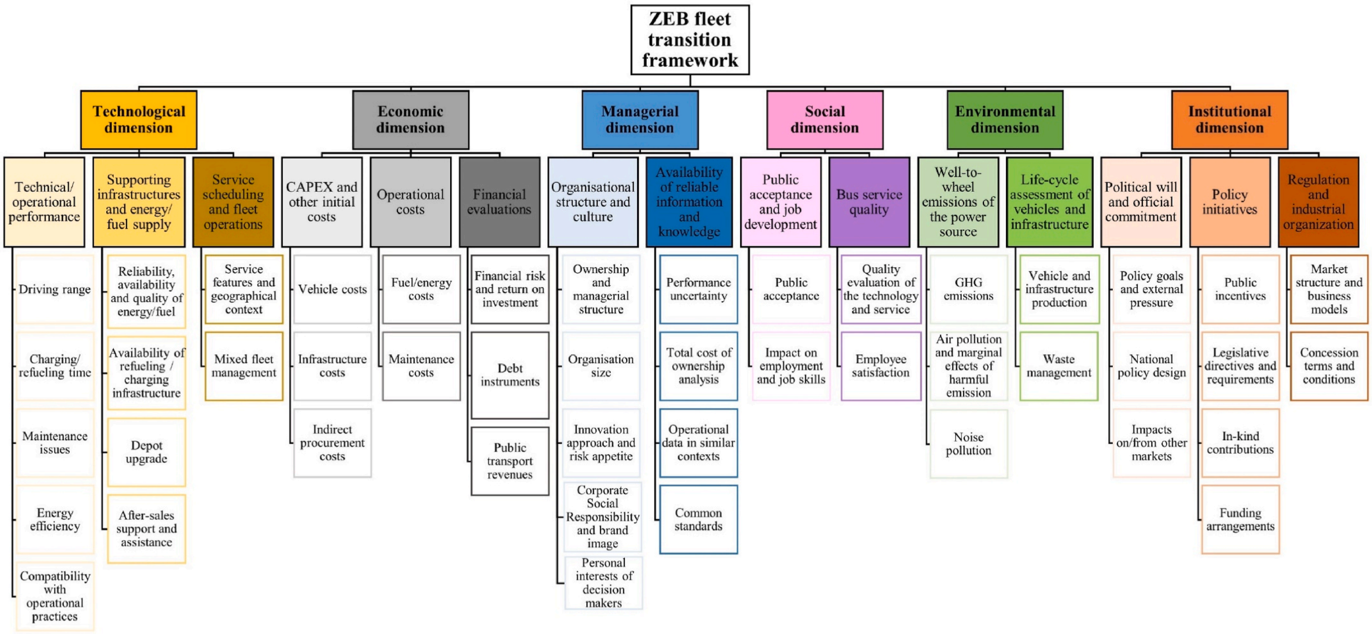

Fig. 2. Hierarchical structure of the ZEB fleet transition framework.

characteristics, supporting infrastructures and compatibility with public transport services.

The first critical issue is the *driving range* limitation linked to battery electric buses, as mentioned in nearly every paper. This directly impacts vehicle flexibility and service scheduling, leading to a degradation of service (at the same cost) and additional operational complexity [53, 54]. However, some studies highlighted that the particular features of public transport (e.g., fixed routes and schedules, centralised depots, shared infrastructures) make transit electrification easier, relative to electrification in private mobility [7]. Manzolli et al. [25] noted that most recent energy management strategies (e.g., dynamic programming) can be efficiently implemented, thereby also improving the useful life of batteries. In general, advanced battery management will improve the effectiveness and efficiency of electric powertrains [55–57]. Aldenius et al. [32] analysed some cases in which opportunity-charging buses were introduced as a solution to the limited range. Hydrogen fuel cell buses increase vehicle range, while also serving as range extenders in hybrid solutions with electric batteries [58].

ZEB adoption poses additional challenges related to *charging/refuelling time*, which also increases operational complexity. Interestingly, there is a trade-off between bus frequency and charging needs, especially for opportunity charging options [59]. Nevertheless, new bus routing and scheduling tools, based on optimisation models, are needed to integrate bus service operations and charging infrastructures [29,60].

Some *maintenance issues* connected with the ZEB transition have also been reported. In particular, battery degradation and the useful life of batteries after the warranty period are concerns for bus fleet owners [59]. ZEBs thus require new safety schemes, which may also impact maintenance operations [29,61,62].

In terms of *energy efficiency*, electric powertrains outperform internal combustion engines, due to their higher engine yield [63]. However, the energy consumption of battery electric buses is more influenced by contextual factors (e.g., speed variation, weather conditions), which may reduce this technological advantage [64–66]. Moreover, bulky tanks or batteries decrease loading ability [54]. However, Thorne et al. [67] highlighted that there is only a small reduction in seat capacity due to the total mass limit of the bus, and this does not affect the load capacity when standing plots are considered.

The final factor identified with respect to the technical sphere was *compatibility with operational practices*. ZEBs require a different operational approach, and the locked-in daily activities of transport providers may slow down the transition [68]. Bae et al. [30] found that investments in a specific fuel option tend to increase the likelihood that the same decision-maker will reject other alternative technologies. In this respect, fuel cell buses may represent a valid alternative, since they do not require frequent recharging and are more similar to conventional fossil fuels [61].

3.1.2. Supporting infrastructures and energy/fuel supply

Supporting infrastructures and energy/fuel supply relate to the accessibility of recharging/refuelling stations, also considering depot upgrades to manage new on-site operations related to ZEBs.

The *reliability, availability and quality of energy/fuel* play a pivotal role in large-scale ZEB deployment. In this sense, transport planners face a set of challenges: the low capacity/willingness of the energy supply chain to deliver power promptly and at the agreed volume [33], grid congestion and priority allocation during electricity shortages [25,69], a limited ability to mass-produce low- or zero-carbon hydrogen [70] and other exogenous risks (e.g., trade wars in the energy/fuel supply chain, dependence on raw materials for electric vehicles). However, there are many industrial ways to reliably produce both green electricity and hydrogen that can be integrated into bus charging/refuelling strategies, such as photovoltaic solar generation [71] and electrolysis for hydrogen [61]. Manzolli et al. [25] highlighted that electrified bus fleets constitute "moving energy storage systems" that can contribute to grid resilience, as buffers to smooth out peak loads. Moreover, the use of ultracapacitors and other smart measures can decrease the maximum power demand [58,59]. Regarding more strategic considerations, Bae et al. [30] noted that the diversification of fuel technologies can alleviate operational risk. Additionally, Vodovozov et al. [61] suggested that several production plants of "green" hydrogen be designed for the coming years. Regarding the resilience of the transit service network, Hensher [72] emphasised the potential unreliability of a public transport system powered only by electricity, as, "if power goes down everything goes down … trains, trams, buses".

ZEB feasibility also depends on the a*vailability of refuelling/charging infrastructure* (e.g., bus chargers, electric grid connections, hydrogen refuelling stations) for bus fleets. This is largely considered a barrier to ZEB adoption due to the challenges involved in installing chargers in dense urban areas (e.g., cable routing on public roads/pavements, power provision), finding spaces for on-site refuelling and maintenance, and meeting parking requirements linked to longer stops [29,70]. In this respect, public and private actors (e.g., transport and energy operators) must cooperate to plan alternative charging strategies in line with city and transit service [67]. While the availability of public infrastructure undoubtedly enables ZEB implementation, bus fleet operators may also rely on central facilities [73,74].

Bus *depot upgrades* are needed to accommodate ZEB infrastructure and operations. Civil work (e.g., excavation, conduits, cabling, repaving) may be required to bring power to bus parking locations, and this may delay implementation [58], over and above any local government approvals [72]. Furthermore, ZEBs require new safety and prevention standards, as health and safety concerns are critical to depot operation. In fact, a higher annual frequency of accidents has been observed in electrified bus fleets due to thermal runaways in battery packs [75,76]. Moreover, hydrogen tends to easily flow out of the tanks [61]. In general, ZEBs require new safety and prevention standards.

Finally, *after-sale support and assistance* for both vehicles and infrastructure may impact ZEB diffusion. In recent years, unknown and distant suppliers, shortages of spare parts and unreliable after-sale services have hindered the large-scale deployment of electric buses [18,77]. However, warranties and maintenance provided by manufacturers have recently been found to facilitate the adoption of alternatively powered buses [30]. In addition, some service providers have started to sell turnkey solutions (i.e., “vehicle-as-a-service”), bundling bus maintenance, charging infrastructure and energy provision into a single charge to the operator [32,33].

3.1.3. *Service scheduling and fleet operations*

Service scheduling and fleet operations may require ZEB technologies to adapt to current transit provision requirements and operations, or vice versa.

In this regard, *service features and the geographical context* may pose various challenges to ZEB diffusion. Indeed, demanding driving regimes related to route topology and bus transit characteristics (e.g., a hilly terrain, slow traffic, frequent stopping, a high load factor, weekly supply variation, extreme weather conditions) may significantly affect efficiency and effectiveness (see, e.g., Refs. [25,31,67,78]). In this regard, public space and urban density play influence electric traction feasibility, especially for trolleybus systems [79]. Conversely, several public transport characteristics match well with ZEB specifications, including fixed daily routes, long idle times for recharge, and small daily variance in the required duty cycles [80]. Studies have underlined the connections between context, battery type and charging strategy for electrified bus fleets [57,74,76]. Local areas with infrastructure available to generate renewable electricity and rural areas that may do so at a lower cost may support the transition to ZEB systems [59,71]. In this context, new computational capabilities related to bus operation planning and scheduling may also help to accelerate ZEB diffusion (e.g., predictive energy consumption management, decision support models) [7,29,81].

These optimisation techniques are key to facilitating effective *mixed fleet management*. Indeed, transport operators are currently challenged to handle different power/fuel sources simultaneously at depots. The integration of practices related to conventional fossil fuels and electric buses may increase management complexity, also considering the expertise of diesel-trained staff [33]. However, reliance on various power technologies may alleviate operational risk by determining the most effective alternatives for specific needs and taking advantage of dynamic pricing models for different power/fuel sources [58,82].

3.2. *Economic dimension*

The economic dimension focuses on the cost performance of ZEBs compared to fossil fuelled buses, focusing on CAPEX and OPEX expenses. Given that ZEB adoption is determined at an organisational level (by both public and private decision-makers, as defined by Biresselioglu et al. [18]), it is crucial to carry out a financial assessment of ZEB technologies.

3.2.1. *CAPEX and other initial costs*

CAPEX and other initial costs refer to all of the capital expenses related to upfront investments and fleet revamping. Regarding start-up expenses, decision-makers must also consider pre-purchase and transaction costs (e.g., the search for and selection of suppliers).

Vehicle costs include bus purchasing costs, midlife costs (e.g., battery replacement), and disposal costs. These costs are considered a significant barrier to ZEB adoption, as they are higher than the comparative costs for buses powered by conventional fossil fuels (see, e.g., Refs. [29,83,84]). Battery costs still account for a considerable share of the vehicle costs [85], and their useful life is approximately half that of internal combustion buses [59]. However, some studies remarked that energy storage hybridisation (i.e., batteries, super-capacitors) can potentially reduce electric bus costs [25,86]. Fuel cell buses are comparatively expensive due to the rare substances needed for their construction, as well as their small-scale production [61].

The other significant investment related to ZEB fleets concerns *infrastructure costs*, including installing and running electric chargers and refuelling stations and modifying depots [87]. Blynn and Attanucci [53] identify potential diseconomies of scale related to electric bus infrastructures, as chargers are often bundled with the vehicle (i.e., electricity upgrades, more depot space).

A thorough economic assessment of ZEBs must also consider *indirect procurement costs*, referring to all expenses and activities that support the effective deployment of the power technology. These are influenced by a lack of brand and model variety, a lack of competition (i.e., higher negotiation costs), the long time needed to develop fruitful collaboration with suppliers, and a lack of operational capabilities [30,32,63]. In many countries, competition among bus manufacturers and energy retailers has been growing, with a positive impact for ZEB fleet development [33].

3.2.2. *Operational costs*

In this framework, OPEX refers to variable costs connected with bus service provision, mainly reflected in fuel/energy and maintenance expenses.

Fuel/energy costs differ substantially between battery electric buses and fuel cell buses. In the first case, they are widely considered an enabler to adoption, due to the lower price of electricity compared to other fuel alternatives [18]. Moreover, transport providers can lever the dynamic pricing of electricity (e.g., lower charges in off-peak periods) by adopting real-time charging scheduling systems, thereby significantly reducing operational costs [7]. The energy demand charge must not be underestimated, since it can significantly increase operating expenses and, especially if load cannot be shifted to off-peak periods, discourage bus fleet electrification [58]. In this context, the implementation of distributed energy generation hubs (mainly powered by solar energy) may cut costs related to grid usage [25]. Conversely, the cost of hydrogen is a key barrier to fuel cell bus diffusion, due to both production and retail expenses [70].

Maintenance costs are quite variable and depend on various subfactors, including the choice of whether to outsource services. Some studies have highlighted maintenance cost savings related to electric bus adoption as a consequence of the reduced number of components (e.g., no emission control equipment or oil changes) [30]. Fuel cell buses, instead, suffer from limited development [83].

3.2.3. *Financial evaluations*

Financial evaluations refer to the impact of ZEBs on the financial performance of fleet owners, considering potential returns on investment and public transport revenues, as well as financial risks.

Financial risks and returns on investment are difficult to predict, since the overall costs incurred by switching to ZEBs are uncertain [32].

However, fleet owners must consider risks associated with over-investing in a particular technology under development (as it could be soon obsolete), sunk costs related to asset-intensive technologies (e.g., ZEBs), cost escalation in contracts, and public funding uncertainty [33,54].

In this context, in addition to the crucial role of public funding (see Section 3.6), the lack of start-up capital might be addressed through *debt instruments*. Particular bonds and soft loans (e.g., green bonds, concessional loans, international climate loans) may help to reduce the cost of financing [77]. Furthermore, long-term solutions may allow third-parties to provide capital assets through leasing schemes [18,67].

ZEB adoption may also impact *public transport revenues*, as some studies have found a positive consumer intention to use electric buses over and above fossil fuelled buses [7]. However, studies have produced mixed findings on whether consumers are willing to pay more to use ZEBs [29,80]. In general, low public transport service revenues are likely to delay investment [87], and it may be necessary to reduce the bus supply in order to fund new ZEB technologies [53]. Recent studies remarked the importance of improving public transport quality and studying users' perceptions [88].

3.3. Managerial dimension

The managerial dimension analyses how organisational characteristics might influence the transition to a ZEB fleet, also considering levels of knowledge about the relevant technologies.

3.3.1. Organisational structure and culture

Attitudes towards alternative bus technologies are affected by organisational factors related to both governance frameworks (e.g., ownership type, managerial structure) and culture and values (e.g., corporate social responsibility, innovation approach).

First, transport providers' *ownership and managerial structures* may influence their ability and propensity to transition to a ZEB fleet. Various studies have found that services that are publicly owned are more likely to adopt ZEBs, due to state-wide regulations and fewer budget constraints [32,73,89]. Also the managerial structure (i.e., autocratic, bureaucratic, democratic, hierarchic) may affect the decision-making process and thus the likelihood of adopting new technologies. Mohammed et al. [28] expanded on this by showing that hierarchic organisations are more likely to be early adopters of alternatively powered buses.

Organisation size is another key determinant of ZEB fleet deployment. Large transit providers tend to have greater financial availability, more operational capabilities (i.e., a large fleet allows vehicle assignments to be rotated), lower energy costs, more opportunities to affect market developments, more familiarity with innovation processes, and more environmentally-friendly brand images [28,80,90,91].

Focusing on organisational culture, fleet owners' *innovation approach and risk appetite* may represent both barriers to and enablers of a ZEB transition. The literature reports an interesting trade-off related to risk appetite: on the one hand, early adopters of ZEBs risk being "guinea pigs" for technological development [80] by investing in assets that are still developing (and could be soon obsolete); however, they may benefit from a first-mover advantage [73]. Miles and Potter [92] claimed that new risk management strategies are important for a successful transition, and Aldenius et al. [32] highlighted that stakeholders face the challenge of managing unexpected outcomes related to innovation. In this regard, lock-in effects and "inertia" linked to the tendency to purchase known and mature technologies may hinder the transition to ZEBs [93,94].

Corporate social responsibility and brand image relate to ZEBs' positive impact on environmental stewardship, which may contribute to a good public image and increase employee morale and efficiency [54]. Indeed, corporate social responsibility is considered a primary motivator for the adoption of clean technologies [30].

Finally, the transition to new technologies may be influenced by the *personal interests of decision-makers*, which may be linked to a wide variety of attitudes, including technophilia, scepticism/conservatism, social pressure, and lack of knowledge [18,28,33].

3.3.2. Availability of reliable information and knowledge

The mass deployment of technology may be challenged by inadequate levels of information and knowledge among stakeholders.

Performance uncertainty is a key barrier to ZEB fleet transition. This implies a lack of reliable knowledge with respect to various service dimensions (e.g., the useful life and driving range of electric batteries, alternative charging infrastructure options and development, maintenance costs, electric system failures, R&D, environmental impacts [28,30,80]). However, the robustness of the bus technology assessments can be improved by developing risk analysis methods [95,96].

While a growing number of studies are conducting *total cost of ownership analysis* of ZEBs, these studies are affected by uncertainty related to a lack of information about some model components, particularly with respect to the vehicle and infrastructure lifetime, future energy costs, maintenance costs, and resale value or disposal costs [29,32,68]. In this regard, over the last decade, ZEB costs have been decreasing due to economies of scale and supply chain development, and further improvements are expected [34]. For instance, the costs of electrolysation have more than halved over the previous decade [61].

Moreover, the lack of *operational data in similar contexts* is still cited as a barrier to ZEB adoption. There is a need for real-world data in connection with challenging routes and large-scale implementation [7,31]. Conversely, considerable data is available from demonstration projects, scientific reports, and case studies [28,63].

Finally, the diffusion of *common standards*, especially related to safe operational procedures, may affect transport operators' knowledge of and attitudes towards ZEB adoption [32].

3.4. Social dimension

The social dimension considers the public acceptance of ZEBs and their impact on the labour market, as well as the perceived quality of ZEBs. The latter is based on the assumption that public transport, given its relevance in terms of accessibility and social equity, is an important component of urban social sustainability [97].

3.4.1. Public acceptance and job development

Public acceptance and job development refer to local residents' opinions and perceptions of ZEBs and the effects of the ZEB transition on employment and job skills.

Positive *public acceptance* and media coverage are often cited as enablers of ZEB diffusion [18,30]. In this regard, environmental factors have been found to influence the choice of travel mode, with consumers that are more inclined to appreciate bus fleet electrification [11]. Conversely, public support for ZEBs is questioned due to uncertainties related to their environmental impact (especially with respect to energy production and battery disposal) and excessive dependence on a specific market (e.g., China [6,68]).

The large-scale deployment of ZEBs may *impact employment and job skills*. Specifically, it may pose new challenges, mostly related to the need for different skills, new performance capabilities and training programs for operational staff (e.g., drivers, maintenance workers) and managers [58,98,99]. Negative downstream consequences may be linked to the limited repair and maintenance regimes required for electric buses and the higher level of automation [6,75]. Conversely, there may be opportunities for new workplaces [100].

3.4.2. Bus service quality

Bus service quality relates to the quality evaluations made by bus drivers and passengers, with respect to the vehicle technology and the service provided.

The *quality evaluation of the technology and service* usually enables

ZEB adoption, as ZEBs have less vibration, run more smoothly and generate less noise, compared to internal combustion vehicles [101, 102]. ZEBs' on-board technology (e.g., WiFi, USB charging ports) and vehicle management tools are also evaluated positively [29,85], though they may give rise to cybersecurity risks [33]. Nevertheless, the frequent charging needs of electric buses can lead to service degradation [54].

Multiple ZEB characteristics positively impact *employee satisfaction* (i.e., drivers). Indeed, ZEBs' better on-board environments (i.e., reduced noise and vibration) may mitigate driver fatigue and improve operational efficiency [30]. While some studies have found that drivers perceive electric vehicles as easy to use and fun to drive [28,82], others have observed that not all drivers wish to drive electric buses, due to range anxiety – also considering that driving behaviour significantly impacts battery performance [67,103].

3.5. Environmental dimension

The primary goal of public policies supporting the ZEB transition is to address climate change and urban pollution within climate action planning, which increasingly needs to be developed consistently with globally accepted criteria, standards, and benchmarks [104]. This recent study also remarks the importance of setting specific, measurable, achievable, realistic and time-bound (SMART) sectoral targets, as well as integrating mitigation and adaptation actions [104]. In this context, the proposed framework includes in the environmental dimension both the emissions of the power source and the externalities related to the entire life-cycle of vehicles and infrastructure.

3.5.1. Well-to-wheel emissions of the power source

Well-to-wheel emissions of the power source relate to environmental impacts due to energy/fuel production and distribution (i.e., well-to-tank) and tailpipe emissions (i.e., tank-to-wheel). In this respect, there are two main categories of harmful pollutants: (a) greenhouse gas emissions (GHG), such as carbon dioxide and methane, which lead to global warming and climate change, and (b) air pollutants, such as particulate matter, nitrogen oxides, and sulphur dioxide, which affect human health and surrounding habitats.

GHG emissions are a controversial issue in relation to ZEB diffusion. The major advantage of ZEB diffusion lies in the emissions abatement during the service provision (i.e., at the tank-to-wheel stage) [78]. However, studies have raised concerns about the production and distribution of electricity and hydrogen, which often relies on fossil sources [61,105]. A growing share of renewable energies is enabling ZEB adoption [7,59]. To this regard, there are different solutions that can help to integrate renewable energy and electric vehicles based on smart charging approaches [106].

Air pollution and marginal effects of harmful emissions are strongly in favour of ZEBs [87], as are reductions in *noise pollution* [30]. ZEBs effectively eliminate harmful emissions of exhaust gases and traditional engine noise. Given that commuter's personal exposure to air pollutants is higher near bus stops [107], the net benefit of the bus fleet electrification may be even greater than expected. However, some side effects should be monitored: Rodrigues and Seixas [29] shed light on the risk of toxic and flammable substance leaks; and Thorne et al. [67] noted that noise improvements may be compromised by HVAC systems and more noticeable charging operations.

3.5.2. Life-cycle assessments of vehicles and infrastructure

Life-cycle assessments of vehicles and infrastructure have received little attention from policy-makers, managers and scientific literature, as highlighted by recent reviews on electric buses [7,25]. Such assessments aim at measuring the cradle-to-grave life-cycle impacts of vehicle components and infrastructures, mostly linked to raw materials (i.e., production) and the end-of-life stage (i.e., waste management). In this context, some studies have raised the issue of environmental pollution generated by *vehicle and infrastructure production* and the *waste management* of vehicle components. Logan et al. [59] asserted that ZEB infrastructure requires a wide range of rare raw materials, whose extraction and export may damage the environment. Equally, the effective reuse and recycling of electric batteries and their compounds remain uncertain [31]. There emerges the need for a wider adoption of circular economy principles in transport sector electrification, so far mainly focused on battery repurposing and remanufacturing [108]. However, other best practices related to vehicle ownership management can contribute to increase the level of circularity in transport industry [109].

3.6. Institutional dimension

Transit services rely heavily on government institutions, which, in addition to providing public subsidies, also influence market structures and technological developments through targeted policy initiatives and economic regulation.

3.6.1. Political will and official commitment

The degree of public intervention is closely linked to political will and the commitment of public authorities, which, in turn, depend on policy goals, national policies and other relevant markets.

Over the last decade, *policy goals and external pressure* have supported the transition to ZEBs. Multiple global and national policies currently promote the adoption of clean vehicles, thereby enabling the adoption of ZEBs [25,110]. In this regard, private fleet owners have expressed concern about political uncertainty and instability [54,111]. Moreover, some policies may hinder upstream competition and slow the market penetration of new technologies (e.g., the Buy America mandate, see Ref. [94]).

Consequently, a coherent and stable *national policy design* is crucial for large-scale ZEB deployment. Local and national policies should be coordinated through a top-down approach, as individual and local initiatives are not likely to generate sufficient impact [77,80,112]. Additionally, integrated urban plans that involve both transport and energy sectors are increasingly relevant [113,114]. Planning should not be static, but subject to systematic review [32]. Board and executive leadership should share knowledge among stakeholders and develop a network of actors to tackle industry issues [53,58,70]. Finally, long-term investment in other technologies (e.g., biogas) may affect (and be affected by) ZEB implementation; given that public transport cannot be powered by only one traction system, a clear direction.

Impacts on/from other markets linked to ZEB diffusion may also influence policy-makers and other high-level decision-makers. Specifically, the large-scale deployment of electric buses may negatively or positively affect electricity grid performance and resilience [29,58]. ZEBs may also contribute to the growth of renewable energies by implementing distributed generation hubs and reducing dependence on fossil fuel imports [54,115]. Finally, at present, the market for electric batteries is heavily dependent on Chinese industry, which is highly exposed to political interference [33].

3.6.2. Policy initiatives

Public interventions generally aim at supporting ZEB diffusion through a variety of targeted policies.

Public incentives are the most common, aimed at reducing purchasing costs relative to conventional diesel buses, and thereby enabling ZEB adoption. Such incentives include capital subsidies (e.g., cash grants to purchase vehicles and infrastructure), tax breaks (e.g., lower registration fees) and direct investment in physical assets (e.g., charging/refuelling stations). Gallo [58] suggested adaptations to the electricity cost structure to accelerate the transition to electric buses (e.g., to remove the grid fee). However, transport operators claim that financial incentives do not make ZEB adoption economically convenient in some contexts [30]. Rodrigues and Seixas [29] asserted that new international sources of climate finance (e.g., Green Climate Fund) may play an important role in increasing funding.

Government actions also depend on *legislative directives and requirements*, such as harmful emission quotas, low-emission zones, vehicle emission limits, and emission-base taxes [61,70,82]. A lack of uniform standards may risk deterring the large-scale deployment of ZEBs [32,99].

Finally, "*in-kind contributions*" [77] from public authorities represent an important ZEB enabler. The literature proposes various examples of these initiatives: pilot projects, information on policy initiatives, support for R&D (e.g., update studies), support for knowledge sharing (e.g., real-world operational data, streamlined guidelines, tutored vehicle trials, formalisation of tacit knowledge, lessons learned and best practices), operator assistance for defining a monitoring plan and training employees, education and awareness campaigns for users, and the introduction of comfortable ticketing systems.

However, public subsidies sometimes remain unused, mainly due to ineffective funding *arrangements*. Blynn and Attanucci [53] noted that it is difficult to comply with public funding schemes based on a fixed amount of money, since buses and infrastructures are complex investments that rarely align with the budget. Aldenius et al. [32] described that, when subsidies are provided after an operator has purchased a ZEB, the operator may not be able to anticipate the payment. Mohammed et al. [28] asserted that purchasing policies restricted to the choice of options from a predetermined list may disincentivise fleet owners who want to forge partnerships with suppliers. Du et al. [76] highlighted the risk of over-subsidising a specific technology without defining an overall strategy based on desired service features. Finally, Miles and Potter [92] concluded that subsidies, alone, are insufficient and that more is needed to support risk management approaches and the organisational structure of public transport.

3.6.3. Regulation and industrial organisation

Regulation and industrial organisation focus on the connection between the economic regulatory framework and the ZEB supply chain.

Institutional innovation is needed to enable appropriate *market structures and business models* for the effective implementation of ZEBs [68]. In this regard, policy-makers face various challenges. First, the adoption of ZEBs in public transport requires a different division of responsibilities between operators and local authorities [32,68]. A complex mix of stakeholders (e.g., energy providers, bus manufacturers) must interact to provide the service [32,67]. Moreover, new market entrants (e.g., charging infrastructure providers) may have little understanding of public transport but hope to profit from their services [33]. There is a clear need for innovative regulation to deal with different stakeholders, ensuring an appropriate distribution of risks and promoting cooperation at all stages, from the planning phase onward [29,34,77]. Hensher [33] proposed a collaborative approach (i.e., "supply chain partnership contract") consisting of a contract or management agreement between a public authority and consortiums that account for the entire supply chain, similar to a public-private partnership. Miles and Potter [92] described a business model in which an "enabling company" purchases buses and chargers and leases them to transport operators.

In this context, the *concession terms and conditions* defined by public authorities must implement an appropriate incentive scheme for all stakeholders. Some elements of current contract rules may affect the smooth transition to ZEBs (see Refs. [67,68,87]): cost efficiency targets and acceptance of potential cost increases, contract length (i.e., the longer lifetime of ZEBs and their infrastructure relative to conventional buses), the importance of environmental criteria, arrangement flexibility (i.e., ZEBs may have start-up problems), incentives for the service provider to innovate (i.e., not only at the bidding/negotiation stage) and rights allocation at the end of the concession period.

4. Assessment of barriers and enablers

This section presents and discusses the results of the quantitative analysis according to the hierarchical structure of the ZEB fleet transition framework (Section 3).

4.1. Systematic collection of barriers and enablers and connection with the holistic framework

The second step of the content analysis was developed by systematically accounting for the barriers to and enablers of ZEB adoption identified in the literature. At this stage, 768 items (i.e., 384 barriers, 384 enablers) were manually recorded through an in-depth reading of the selected articles. These barriers and enablers were connected to one or more sub-factors of the proposed holistic framework. The result was an interaction matrix consisting of 46 columns (i.e., the sub-factors of the ZEB fleet transition framework) and 768 rows (i.e., the barriers and enablers extracted from the reviewed literature), where the cell value is 1 is the sub-factor is affected by the item, and 0 if not. Consistently with hierarchical structure of the framework, the columns of the matrix can be aggregated in the 15 decision-making factors and in turn in the 6 evaluative dimensions. This matrix constituted the analytical basis for conducting quantitative analysis on the frequency with which each decision-making factor/sub-factor was identified as a barrier or enabler in the reviewed literature. These descriptive statistics allow drawing an overview of the impact – intended as influence direction (i.e., hindering or enabling) - of the decision-making factors included in the framework on the large-scale deployment of ZEBs, as well as taking into account the effects of technology progress and improved managerial practices.

4.2. Impact of the decision-making factors

The first main finding referred to the contextuality of the deterring or motivating effect on ZEB adoption. The analysis collected information on the same barriers and enablers in different economic and cultural contexts, and different time periods. Some factors were considered barriers in some studies and enablers in others, depending on the geographical context, the national governance, the public transport organisation, the degree of technological development and the relevant stakeholders. This implies that there are continuous trade-offs between conflicting multi-criteria dimensions in the decision-making process, which might be strongly affected by local circumstances. For instance, Aldenius et al. [32] noted significant differences in the challenges related to electric bus adoption between four cities (in UK and Sweden), while Barfod et al. [82] found a mismatch between fleet managers and policy-makers regarding the importance of some factors. Mahmoud et al. [26] assessed techno-economic competitiveness of different electric powertrain options adopting a multi-criteria approach.

Figs. 3 and 4 show the impact of each evaluative dimension and the related factors and sub-factors, based on the reviewed literature.

ZEBs' low technological performance is mainly due to their decreased flexibility and corresponding greater operational complexity. All of the reviewed studies identified the limited driving range of battery electric buses as a critical issue, in addition to the need to recharge (both overnight and during service). This implies a greater need to define service scheduling to achieve the correct trade-off between bus frequency, recharging time and impact on the electricity grid. In this regard, the other two major barriers that were identified in the literature relate to the availability and reliability of supporting infrastructures and energy. With respect to this last point, the main challenge refers to ZEBs' high-power loads. After the grid connection is built, the electric market is less volatile than the fossil fuel market. Service features and the geographical context may hinder or facilitate the transition to ZEBs, according to local conditions.

With regard to the economic sphere, the high capital costs related to vehicle purchasing, infrastructure development and other initial costs

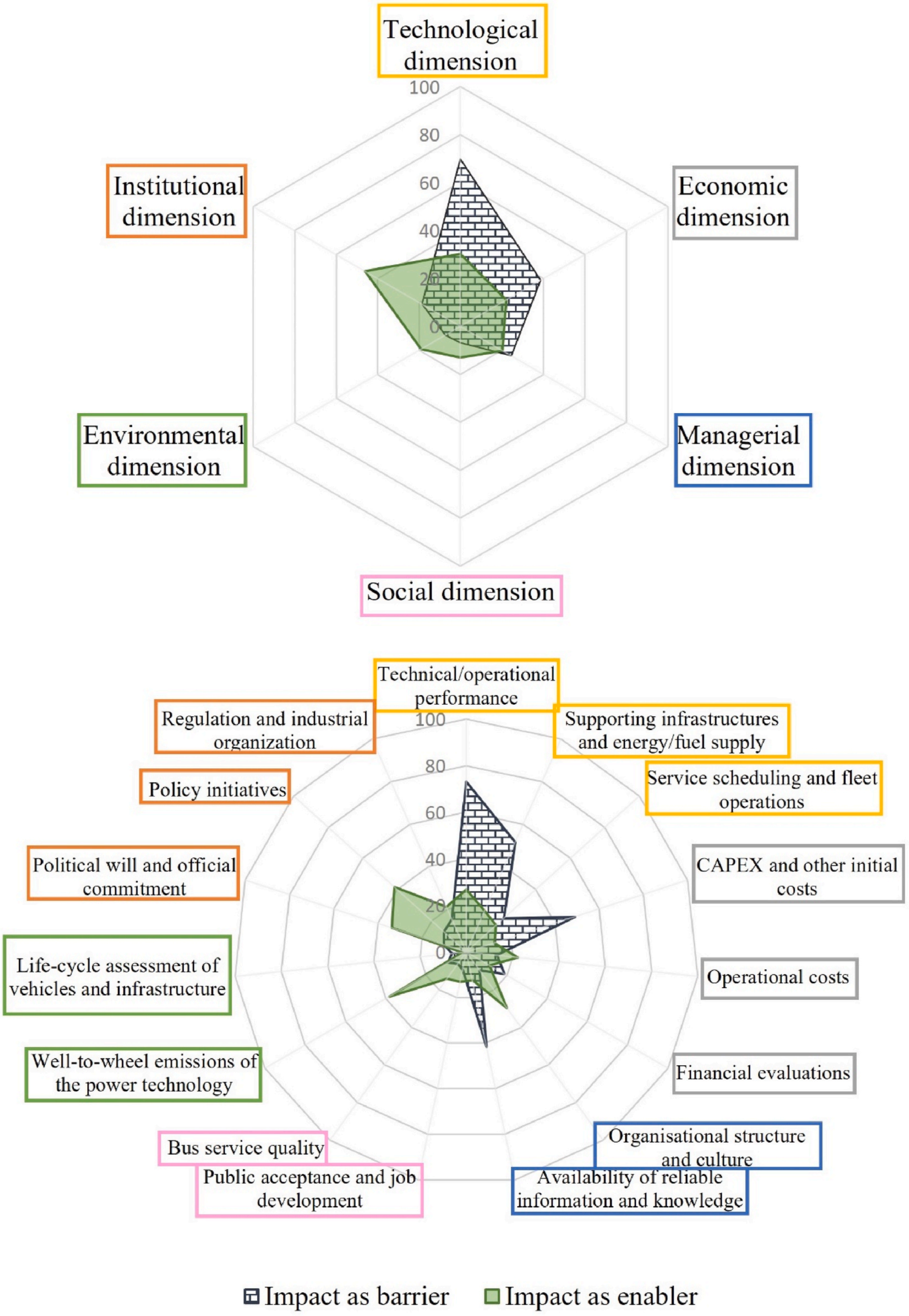

Fig. 3. Impact of the evaluative dimensions and related factors*. * The numerical scale indicates the total number of mentions as barrier/enabler of each dimension/factor (normalised to 100). For instance, the factor related to the Technical/operational performance was mentioned as a barrier in 128 instances (73%) and as an enabler in 47 instances (27%). The radar chart is scaled based on the most cited dimension/factor in order to provide a graphical view of the relative frequency with which the influencing factors are mentioned in the literature. Note that the total number of mentions of each dimension is the sum of the mentions of its component factors, which in turn is the sum of the references of the related sub-factors (Fig. 4).

(including indirect costs) represent another major barrier to ZEB adoption. This cost structure makes investment in ZEB fleets risky, due to the long payback period and the relative immaturity of the technology (especially with respect to fuel cell buses). The cost-effectiveness of battery electric buses (in terms of operational costs), mainly due to lower energy costs, plays an important enabling role by compensating for the higher initial expenses. Moreover, alternative debt instruments for fleet owners (e.g., green bonds, leasing schemes) may contribute to

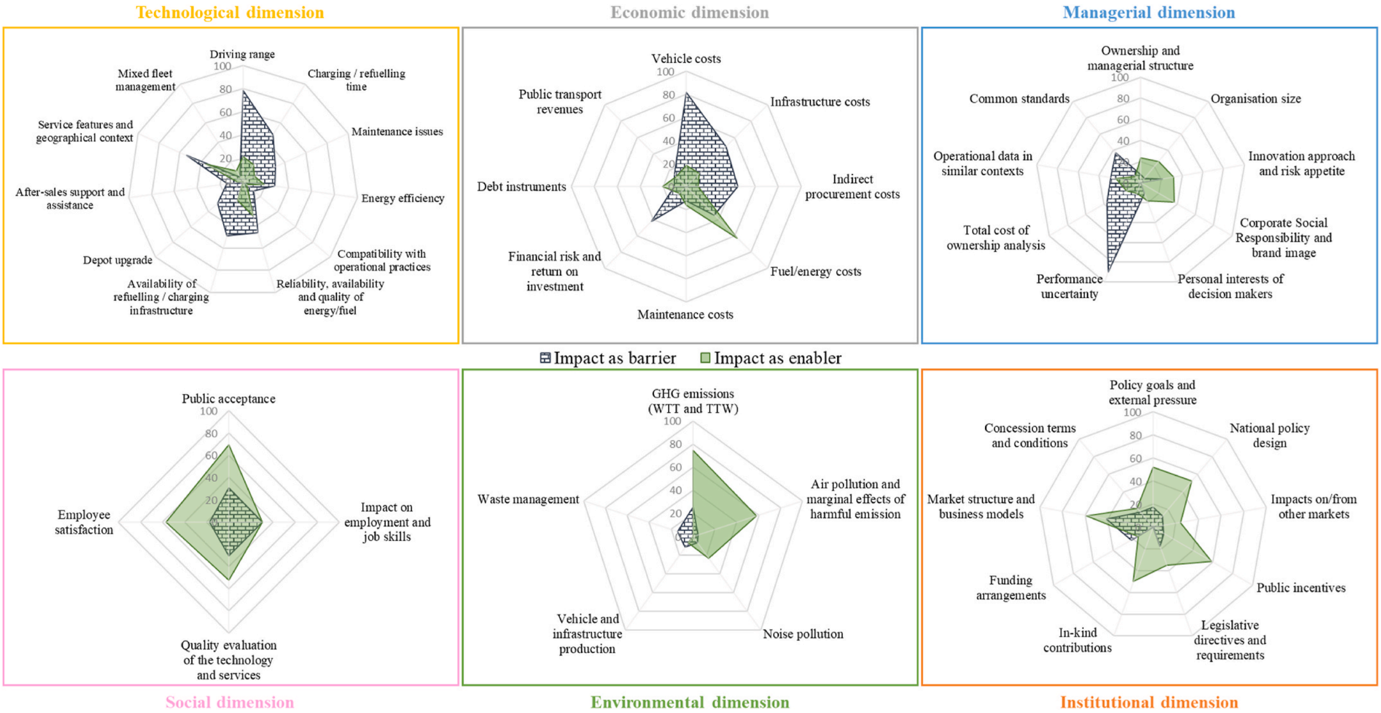

Fig. 4. Impact of each factor and related sub-factors*. * The numerical scale indicates the total number of mentions as barrier/enabler of each sub-factor (normalised to 100). For instance, the sub-factor related to the Driving range was mentioned as a barrier in 51 instances (78%) and as an enabler in 14 instances (22%).

reducing the impact of the high upfront costs, even if these were not frequently cited in the literature.

The managerial dimension is influenced by two opposing factors: the lower availability of reliable information (identified as an influential deterrent to ZEB diffusion) and the organisational structure and culture of stakeholders (often cited as an enabling factor). Regarding the latter, transport operators often refer to corporate social responsibility as one of the main reasons for their switch to ZEBs. Organisational size may also play an important role by influencing financial availability, familiarity with innovation processes and attention to the company image. Indeed, many fleet owners stress the importance of being large enough to effectively manage this transition process. The fact that these aspects were highlighted more frequently as enablers than barriers suggests a likely bias in this stream of the literature, which is predominantly focused on case studies of adoption, rather than non-adoption decisions. Consequently, the participating managers reported their organisational environment, innovation approach and personal interest as facilitating factors. However, a closer examination of non-adoption decisions may find that these factors can also play the opposite role.

Conversely, knowledge about ZEB technologies was identified as an important barrier to their deployment, mostly due to uncertainties related to operational performance (e.g., battery durability and lifetime, charging procedures, maintenance costs) and thus the total cost of ownership. Also, a lack of common standards often negatively impacted adoption decisions. Practical operational data are growing, but only based on pilot projects and cases of small-scale implementation; further research on the effects of large-scale deployment is needed.

While the social dimension was the least studied in the literature related to alternative bus technologies, it is gaining importance in decision-making processes, especially from a public policy perspective. The factors related to social criteria seemed to support ZEBs. These included public acceptance (linked to ZEBs' green image), employee satisfaction (related to driver-friendliness) and service quality (e.g., on-board comfort). However, the large-scale adoption of ZEBs may have a disruptive impact on staff skills and competencies, especially with regard to maintenance and depot operations; this impact may both negatively and positively affect employment levels.

The environmental dimension represents the main motivation for switching to ZEBs (i.e., to reduce road transport pollution). The tank-to-wheel emissions of alternative bus powertrains (GHGs and air pollutants) have been extensively studied in both academic and grey literature. While there is no doubt that ZEBs cut harmful emissions from the tailpipe, their carbon footprint related to the well-to-tank stage depends on the source of their electricity or hydrogen energy. Nevertheless, the overall reduced environmental impact of the power technology is considered an enabler of the transition to ZEBs, also considering their reduced noise pollution. Conversely, life-cycle assessments of ZEBs show negative downstream consequences due to the wide use of raw material sources that are rare and difficult to dispose of or recycle. However, the precise impact of this latter factor is unknown, as there is little research on it.

Over and above the environmental dimension, the institutional dimension has been the most mentioned enabler for ZEB adoption. Most of the reviewed studies focused on the decision-making processes related to ZEB deployment, made by fleet owners (mostly private transport operators or transit agencies). These most often referred to policy initiatives and the need to comply with environmental regulations, rather than the perceived importance of reducing emissions (i.e., corporate social responsibility). In this framework, policy goals and external pressure, coordinated national policies, public incentives, legislative directives and in-kind contributions may play a crucial role in promoting ZEB diffusion. Of note, policies must be effectively designed and planned in order to achieve targets. However, in some cases, funding arrangement schemes were identified as barriers to ZEB adoption, making it difficult to access grants or cover expenses other than the purchase of vehicles. The enabling impact of institutional criteria was less evident with respect to economic regulation and industrial organisation. Indeed, the need for new collaborative governance frameworks, new divisions of responsibilities and risks between stakeholders, and new concession terms and conditions related to public transport services provided by ZEBs has not been consistently met by local authorities. The reviewed studies presented several examples of ZEB deployments in which policy-makers set up appropriate market structures to support the development of new business models. However, these factors were not considered in many decision-making processes, thereby limiting the adoption of ZEBs. In this respect, research on regulatory conditions that may facilitate the large-scale implementation of ZEBs is needed.

In conclusion, the transition to a ZEB fleet may be hampered by technological, economic, and managerial factors. Conversely, social, environmental, and institutional criteria are likely to support the adoption of alternative bus technologies. The hindering impact of technological, economic, and managerial dimensions explains why transport providers, who are subject to budget constraints, are often reluctant to switch to ZEB fleets. In contrast, new entrants to the industry, such as energy and infrastructure providers (other than bus manufacturers), tend to look for opportunities related to ZEB diffusion with interest. Public authorities are promoting ZEB diffusion to achieve sustainable development goals, particularly within environmental and social dimensions. However, they are challenged in their efforts to create incentive systems that facilitate the necessary market structure and business models for ZEB fleets.

4.3. Time trend effects on decision-making factors

Technology and practices improve over time, due to technological advancements and the typical learning curve that applies to the production and use of products. With respect to the ZEB fleet transition, this progress may involve all evaluative dimensions (e.g., increased electric battery performance, reduced costs, greater availability of information, greater knowledge about environmental protection, a growing share of renewable energies, new forms of public-private partnerships). It follows that unmet functionality, availability, and/or economic issues may be based on outdated assessments.

This review included articles published over a 25-year time span. Within this time, the relevance of many factors changed, according to technological developments. However, the sample of papers was not uniformly distributed: more than half referred to the last 3 years (52% in the period 2019–2022) and relatively few were published prior to 2008 (8%). To analyse the time trend effects on factors influencing the transition to ZEBs, the reviewed studies were split into two groups: (1) those published before and in 2018 and (2) those published after 2018. Subsequently, the potential differences in the reported impact of each factor between groups were investigated. There are two reasons behind the choice of 2018 as the dividing point: first, it could be considered the breakthrough year for ZEBs in Europe: in 2019, new electric buses registrations tripled, compared to the previous year; and the total number of ZEBs went from approximately 1650 vehicles (2018) to more than 3660 (2019) and up to 9500 (2022) in the EU [16]; second, it split the set of articles in half, illustrating how research in this area has grown in line with the market share and policy commitment to ZEBs.

The comparison between the two sets of studies was based on the frequency with which each sub-factors was mentioned as barrier and enabler in relation to the total number of mentions of each sub-factor respectively (Fig. 5).

The overall picture showed an optimistic trend, considering studies published after 2018, with barriers decreasing and enablers increasing

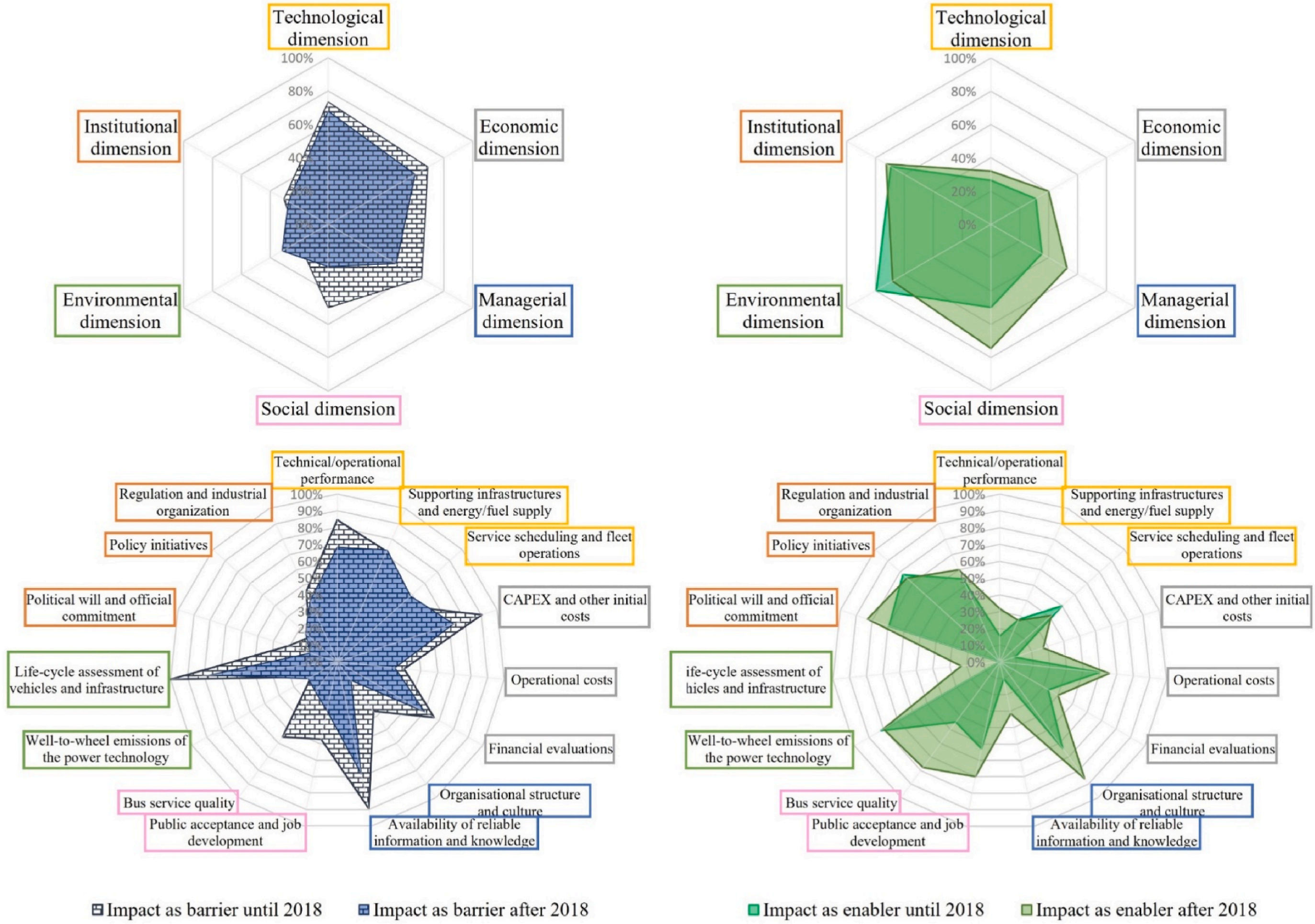

Fig. 5. Comparison of the percentage share of mentions as barriers and enablers for each dimension/factor up to and after 2018*. * The numerical scale indicates the percentage of mentions as a barrier and enabler of each dimension/factor.

in number of mentions by the literature (except for those within the environmental dimension).

Progress related to electric battery durability seemed to significantly reduce the negative impact of operational performances related to electrified bus fleets, leading to a general improvement in the technological dimension evidenced in the studies published after 2018 (even though electric battery durability still remained a main barrier to ZEBs adoption). However, focusing on specific factors, deterrents associated with infrastructure, depot operations and service scheduling seemed to increase in impact. This was expected, given the higher operational complexity of both service provision and charging management, and the lack of electricity power (i.e., critical issues linked to the switch from small-scale to large-scale ZEB deployment).

The economic dimension showed a promising trend, with the impact of CAPEX and other initial costs as barriers to ZEB adoption decreasing. This suggests that, over time, fleet owners have considered investment in these technologies less risky. In addition, the enabling impact of lower energy costs rose, perhaps due to the escalation in fossil fuel costs.

The most noticeable improvement referred to the managerial dimension, which demonstrated a reverse in the influence direction after 2018. It is likely that the growing availability of operational data and shared experiences reduced the relevance of barriers related to the reliability of information. Moreover, Corporate social responsibility became more important within organisations after 2018, thereby increasing the impact of organisational structure and the culture of transport operators as enabling factors.

The social dimension also grew in relevance, typically in support of ZEBs. Indeed, ZEBs increasingly earned the appreciation of bus passengers and drivers, who developed greater confidence in the ZEB service supply and connected ZEBs with healthy urban living.

Conversely, some downstream consequences emerged in relation to the environmental impact of ZEBs – mainly linked to the well-to-tank stage of electricity/hydrogen supply (i.e., energy production and distribution) and the manufacturing and disposal of some vehicle components (i.e., electric batteries, fuel cells). Consequently, after 2018, fewer studies highlighted only the environmental benefits of ZEBs, and the environmental dimension assumed an overall less enabling impact.

Finally, the institutional dimension remained the main motivating factor for ZEB adoption. Policy initiatives aimed at reducing harmful emissions from road transport vehicles increased in number, and studies in both groups reported the efforts of local authorities to deal with the large-scale implementation of ZEBs.

5. Conclusions

This research aimed at building a comprehensive framework to assess large-scale deployment of ZEBs. In line with the most common theories on the diffusion of technological and environmental innovations, the result was a hierarchical structure consisting of 6 evaluative dimensions, 15 decision-making factors, and 46 sub-factors. It emerged that the decision-making process involves continuous tradeoffs between the multi-criteria dimensions, which are also affected by local contexts and stakeholder perspectives. In a second step, the barriers and enablers identified in the reviewed literature were quantitatively analysed to assess the influence direction of each factor on ZEB diffusion. The results showed that technological, economic, and managerial dimensions have hindered the large-scale deployment of ZEBs, while social, environmental, and institutional factors have stimulated ZEB adoption. The time trend analysis showed an optimistic trend due to technological progress and scale economies related to ZEBs' operational and economic performance (with respect to, e.g., batteries and related infrastructure).

Based on the proposed framework, the following topics are of increasing importance for the transition to ZEBs and not fully addressed in the literature. Therefore, future research should aim at exploring these areas, in depth.

- Public transport revenues: investigating whether and how the adoption of ZEBs might affect public transport demand, which is often the first source of funding for bus operators and a key enabler of investment in ZEB technologies.
- Life-cycle assessment of buses, components, and related infrastructure to enable circular business models in transport sector: evaluating the environmental impact of ZEB technologies, also considering externalities related to the production and disposal of vehicles, their components (e.g., electric batteries, fuel cells), and supporting infrastructures.
- Mixed fleet management: exploring the transition to ZEBs is a gradual process, during which transport operators may face the challenge of simultaneously managing different power technologies, often at the same depot. This may introduce greater complexity, also with respect to staff skills and competencies.
- Regulatory framework: assessing how different funding policies and regulation may impact the development of appropriate market structures and business models for large-scale ZEB deployment. In this context, collaboration among stakeholders and flexibility in transport planning are crucial to manage uncertainties concerning the transition.

The proposed framework may support both policy-makers and private operators in their efforts to holistically plan the transition to ZEBs, providing an overview of the main conflicting criteria that should be addressed and managed. Moreover, it represents a starting point for conducting multi-criteria assessments of alternative bus technologies or comparing multiple case studies of fleet renewal projects. Finally, extending the analysis to encompass both private vehicles and freight transport opens new possibilities for comprehensive assessments of transport decarbonisation. The integrated study of electrification across private vehicles, freight transport, and public transport emerges as a promising avenue of research.

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.

Data availability

Data will be made available on request.

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