

Evaluating alternative fuels for a bus fleet: An Italian case

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ABSTRACT

A current topic that has surfaced among Public Transport Companies (PTCs) is the selection of alternative fuels for their bus fleets. Both European and Italian regulations are pushing toward abandoning diesel fuel and the consolidation of alternative traction power sources, such as battery-electric vehicles, fuel-cell electric vehicles, and hydrogen-electric vehicles. The literature has provided some approaches toward assessing this selection such as multicriteria-decision-methods in some countries in the world. However, not enough specific attention has been paid to cost criteria, experts involved, and the type of service required. This paper intends to address these gaps by applying an integrated method, which includes: (i) the Analytical Hierarchy Process (AHP) to define the weights of criteria; (ii) the ELimination Et Choix Traduisant la REalité I (ELECTRE I) to find a good compromise solution among the fuel alternatives and (iii) a simple Weighted Sum Model (WSM) to refine ranking. This integrated method was applied in Italy involving a panel of experts from whom the data was collected. Different fuel alternatives for both urban and interurban services and with and without funding are discussed. The results provide a useful tool supporting PTC policies, which aims to rationalise and prioritise bus fuel alternatives when deciding on fleet renewal.

1. Introduction

In recent decades, concern has been growing about pollution, consumption of fossil fuels, oil depletion, increasing costs of fuel prices, and the impact of CO₂ emissions on the climate (Aydin and Kahraman, 2014). Transportation tends to largely exacerbate the current situation: CO₂ produced by transport vehicles on roads, in the air, in water, by rail, and by other modes accounts for 71.7%, 13.9%, and 13.4% 0.5% and 0.5% of carbon emissions, respectively (Carnevale and Sachs, 2019). Therefore, several governments are defining goals, strategic plans, and legislation to address pollution and decreasing energy resources and their effects on the transport sector. For instance, the European Union has decreed that climate neutrality should be achieved by 2050, the reduction of greenhouse gas emissions by at least 55% by 2030, and the elimination of gasoline and diesel fuel vehicles by 2035 (European Union, 2021). Public transportation systems, such as buses, are themselves a move forward towards the goal of decarbonisation due to their positive effects on pollution and traffic congestion since they decrease

private mobility in urban and interurban areas. They combine climate and environmental protection while ensuring the economic and social balance of countries (Carnevale and Sachs, 2019). However, many of these systems are generally characterised by vehicles that are powered by internal combustion engines (e.g., diesel), with different performance and emission characteristics (Geng et al., 2013; Tong et al., 2017). Therefore, some authors have evaluated alternative energy sources for buses, such as battery electric vehicles (BEV), Compressed Natural Gas (CNG), and hydrogen electric vehicles (HEV) (e.g., Tzeng et al., 2005; Ally and Pryor, 2007; McKenzie and Durango-Cohen, 2012; Borghetti et al., 2022). Public Transport Companies (PTCs) play a crucial role in planning and implementing policies and strategies that encourage alternative fuels in bus fleets (Xylia and Silveira, 2017). Still, introducing city buses powered by alternative fuels represents a significant investment for PTCs: firstly, their need for fleet renewal aimed towards more sustainable and performing fuels, and/or secondarily, the building of related and possible infrastructure, e.g., in BEV with charging station systems (Vahdani et al., 2011). Hence, the need to support the

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decision-making process of a PTC that intends to renew its bus fleet is crucial. Moreover, in deciding on a viable fuel alternative, most PTCs consider funding, purchase and operation costs as the main decision variables (Gerbec et al., 2015), i.e., the main barriers to increasing alternative fuels.

The literature indicates that there are usually several approaches to evaluate and rank alternative fuels for bus fleets such as Multicriteria Decision Making (MCDM) (e.g., Lanjewar et al., 2015; Büyükožkan et al., 2018; Hamurcu and Eren, 2020; Ozdagoglu et al., 2022), Life Cycle Assessment (LCA) (e.g., Graham et al., 2008; Lajunen and Lipman, 2016; Tong et al., 2017; Nordelöf et al., 2019), Cost-Benefit Analysis (CBA) (Lajunen, 2014; Gerbec et al., 2015) and road tests (Keramydas et al., 2018; Gong et al., 2020). Yet clearly, some attention should also be given to the following issues: (i) most of the studies have based their evaluation on specific geographical and operational features, and the methodologies adopted might be difficult to reproduce in other situations; (ii) except as indicated by Gerbec et al. (2015), the cost analysis appears to have been overly simplified; and (iii) the perspective of PTCs has not yet been fully elucidated.

This study aims to address these issues using an integrated method for the evaluation and (possible) ranking of several fuel alternatives for buses (e.g., Diesel, BEV, HEV) to provide a high-level direction for PTCs engaged in (possible) fleet renewal. This assessment was performed for vehicles (currently on the market) to be deployed in urban and inter-urban settings and to be considered during future planning pursuant to European Directives and policies under the Green Deal objectives. This method is being positioned within the framework of a multi-criterion decision problem (MCDM), owing to numerous conflicting criteria and multitude of alternatives. Additionally, the criteria (and corresponding sub-criteria) primarily concern investment, maintenance, and operation costs because (i) they represent a pivotal issue in PTCs and (ii) to our knowledge, no research has been carried out using these refined criteria. Moreover, costs of alternatives were considered both with and without funding. Thus, the innovation lies not in the methodological approach per se but rather in the distinct emphasis on cost criteria, a topic that, to date, has been somewhat disregarded in the literature. Two additional criteria i.e., the lifecycle of a vehicle and the related CO₂ emissions were also considered.

Specifically, the Analytical Hierarchy Process (AHP) was employed to determine the weights of these criteria. Then, the ELimination Et Choix Traduisant la REalité I (ELECTRE I) method was utilised to find a good compromise solution among the alternative fuels for buses. Finally, a simple Weighted Sum Model (WSM) was applied to refine the ranking. This integrated method was then applied in an Italian context, where the results could be viewed as a useful tool in support of PTC policies looking to rationalise and prioritise bus fleet alternative fuels when deciding on fleet renewal. An additional advantage is that the suggested method can be implemented and replicated in other contexts.

The rest of the paper is as follows. Section 2 delves into a review of the literature on bus fleet selection. Section 3 illustrates the integrated method, whilst Section 4 shows the most promising set of fuel alternatives using a real application in Italy as an example. Section 5 discusses the results in the context of the literature, and then Section 6 outlines the conclusions and provides future perspectives.

2. Literature review

Table 1 summarises the results of the main existing studies and shows that there are several approaches to evaluate fuel alternatives for a bus fleet, the experts involved, and the different types of fuels considered as well as criteria (or indicators) adopted. Moreover, the best alternative is identified (if any).

Four approaches were considered during the literature review. The first concerns the Multi-Criteria Decision-Making methodologies or their Fuzzy extensions which are integrated. Hamurcu and Eren (2020) applied an integrated AHP to TOPSIS to evaluate six potential BEV

alternatives for sustainable and ecological urban transport in Ankara (Turkey). AHP measured the weights of the criteria, and TOPSIS ranked the alternatives. Similarly, Büyükožkan et al. (2018) used TOPSIS for ranking fuel alternatives in Istanbul (Turkey). However, the interactions and dependencies among the decision criteria were defined by an integral Choquet method supported by a Group Decision-Making approach applied in an Intuitionistic Fuzzy environment. Conversely, Vahdani et al. (2011) evaluated the traction power supply alternatives using Fuzzy TOPSIS for the weights of the factors and the Fuzzy Preference Selection Index (PSI) for selecting alternatives. Tzeng et al. (2005) used the AHP to evaluate the weights and rank alternatives through the VIKOR method for selecting alternative fuel buses for urban areas of Taiwan. Similarly, Aydın and Kahraman (2014) used the two methods with “fuzzy” logic in the context of Ankara (Turkey) and applied sensitivity analysis to reinforce the results obtained. Lanjewar et al. (2015) evaluated the performance of transportation fuels using a hybrid method, Graph theory and AHP. Recently, Ozdagoglu et al. (2022) applied new multi-criteria methodologies to choose the best alternative among three preferred brands of bus manufacturers for intercity transport in Turkey. The authors applied PIPRECIA criteria to calculate the weights and the COPRAS-G method to classify bus brands.

The second approach focused on the choice of alternative environmental consequences of one bus over another. The evaluations were focused using the environmental and economic Life Cycle Assessment (LCA), which incorporated several fuel consumption components (i.e., well-to-wheels, well-to-pump, pump-to-wheels) and the vehicle cycle (Xu et al., 2015). Most of these studies assessed the life cycle costs (purchase and operation) and different types of emissions and air pollutants, whether direct and/or indirect, e.g., GHG, NO_x, THC, PM₁₀, CO₂, CH₄, CO, VOC, SO_x, and noise (McKenzie and Durango-Cohen, 2012; Cooney et al., 2013; Lajunen and Lipman, 2016; Tong et al., 2017; Nordelöf et al., 2019). Other studies used the LCA to assess the overall environmental footprint and the energy or fuel demand of different types of bus traction power supply (Ally and Pryor, 2007; Ou et al., 2010; Kliucininkas et al., 2012; Ribau et al., 2014).

With similar goals, certain other authors used some interactive modelling tools to facilitate their assessments. For example, Geng et al. (2013) used International Vehicle Emissions (IVE) to calculate vehicle emissions on a macro, meso, and micro scale, to determine the environmental advantages and economic challenges involved in converting fleets to greener technologies. Then, Xu et al. (2015) used the Transit Fuel and Emissions Calculator (FEC) to compare the performance of multiple alternative fuels for the city of Atlanta, Georgia. Still others have performed emission assessments of different bus technologies through laboratory tests (Graham et al., 2008). Finally, Hellgren (2007) applied the Tool for Hybrid Electric Powertrain Synthesis (THEPS) to evaluate the economic advantage of technological choices and how the increase in the price of fossil fuels influenced their choices.

The third (somewhat more limited) approach focused on Cost-Benefit Analysis (CBA). From this perspective, Lajunen (2014) analysed the energy consumption and cost-benefit ratios (in terms of operational management) of various BEV and HEV city bus configurations. Gerbec et al. (2015) enhanced the CBA for the public bus fleet in Ljubljana (Slovenia) to determine the most interesting alternatives and to help PTCs' decision-making in future choices.

Finally, the last approach addressed the challenge of choosing bus types using methods based on road tests. For example, Gong et al. (2020) developed the method of selecting a BEV bus for the city of Nanjing (China), which included standardised training for the drivers engaged in the process. Keramydas et al. (2018) tested different bus fuel alternatives in the city of Hong Kong by considering the emissions produced through a commercially available Portable Emissions Measurement System (PEMS) under average driving and operating conditions.

The involvement of experts only concerned the MCDM approaches, whilst academics, bus manufacturers, bus owners, transport planners, bus riders, and PTCs were surveyed (Tzeng et al., 2005; Aydın and

Table 1
Summary of studies of bus fleet evaluation and selection.

| Source | Country of Study | Method | Experts (#) | Bus Type | Indicator | 1° choice |
|-----------------------------------|------------------------------|------------------------------|--|---|--|-----------------------|
| Ozdagoglu et al. (2022) | Turkey | PIPRECIA, COPRAS-G | Expert bus riders (>10 years) (2) and bus owner (2) | Mercedes-Benz Travego, Man Lions Coach, Temsa Maraton model | Services, Fuel Consumption Cost, Common Spare Parts, Luggage Space, Max Torque, Brand Reputation/Protecting own value in the market, Displacement, Rated Output, Permissible Total Weight, Length | Mercedes-Benz Travego |
| Hamurcu and Eren (2020) | Undefined | AHP TOPSIS | Academics (4) and transport planners (3) | E | Passenger capacity, Speed, Battery capacity, Range, Maximum Power, Charging time | EV_2 |
| Büyükoçkan et al. (2018) | Istanbul (Turkey) | IFCI Choquet integral TOPSIS | Experts (3) not specified | D, CNG, LPG, MET, HEV, EEB, HEV-D, HEV-CNG | Energy availability, Air pollution, Energy efficiency, Noise pollution, Purchasing cost, Operating cost, Road capacity, Vehicle capacity, Passenger comfort, Traffic flow conformance | LPG |
| Lanjewar et al. (2015) | – | Graph theory AHP | Undefined | D, CNG, LPG, HEV, MET, BEV, EEB, HEV-G, HEV-D, HEV-CNG, HEV-LPG | Energy efficiency, Energy supply, Air pollution, Industrial relationship, Noise pollution, Costs of maintenance, Costs of implementation, Vehicle capability, Sense of comfort, Speed of traffic flow, Road facility | EEB |
| Aydın and Kahraman (2014) | Ankara (Turkey) | Fuzzy AHP, Fuzzy VIKOR | Experts (3): Academic (1), TpC (1), Bus manufacturing (1) | D, CNG, BEV, HEV-G, HEV-D, HEV, BD, G | Initial cost, Maintenance cost, Vehicle life, Range, Fuel Cost, Energy efficiency, Fuel availability, Air pollution, Reduce emission, Dematerialization, Safety, Performance, Vehicle capacity, Sense of comfort, User acceptance | CNG |
| Vahdani et al. (2011) | Undefined | Fuzzy TOPSIS FPSI | General Decision makers (3) | D, CNG, LPG, HEV, MET, BEV, EEB, HEV-G, HEV-D, HEV-CNG, HEV-LPG | Energy efficiency, Energy supply, Noise pollution, Air pollution, Industrial relationship, Costs of maintenance, Costs of implementation, Speed of traffic flow, Road facility, Sense of comfort, Vehicle capability, Industrial relationship, Energy efficiency, Energy supply, Noise pollution, Air pollution, Costs of maintenance, Costs of implementation, Speed of traffic flow, Road facility, Vehicle capability, Sense of comfort | D |
| Tzeng et al. (2005) | Taipei (Taiwan) | AHP VIKOR, TOPSIS | Experts (BEV bus manufacturing, academics, research organisation, bus operations sectors) (n. undefined) | D, CNG, LPG, HEV, MET, BEV, EEB, HEV-G, HEV-D, HEV-CNG, HEV-LPG | Industrial relationship, Energy efficiency, Energy supply, Noise pollution, Air pollution, Costs of maintenance, Costs of implementation, Speed of traffic flow, Road facility, Vehicle capability, Sense of comfort | HEV-G, EEB |
| Nordelöf et al. (2019) | Sweden, EU, USA | LCIA | – | BEV, D, BD, HVO, HEV-D, HEV-HVO | Human toxicity (carcinogenic and non-carcinogenic), Climate change (GWP 100), Eutrophication (marine end compartment), Acidification, Particulate matter, Abiotic resource use (mineral and non-renewable), Photochemical ozone formation, | E |
| Tong. (2017) | USA | LCA | – | D, BD, HEV-D, CNG, LPG, EEB | Life cycle ownership costs (purchase costs, fuel costs, vehicle costs, upfront infrastructure costs), Life cycle external costs as GHGs (CO ₂ , CH ₄ , N ₂ O) and CAPs (NO _x , CO, VOC, PM, SO ₂) | EEB |
| Graham et al. (2008) | Canada | Laboratory testing | – | D, CNG, HYT | Fuel consumption, CO ₂ , CH ₄ , N ₂ O | CNG, HYT |
| Lajunen and Lipman (2016) | Finland and California (USA) | LCA | – | D, CNG, HEV-D, EEB, E, FCEV (hybrid and full) | Purchasing cost, Operational cost, CO ₂ | HEV-D, E |
| Xu et al. (2015) | Atlanta, GA (USA) | FEC | – | G, D, CNG, BD (2, 5, 10, 20%), E, FCEV | Meteorology and terrain roughness processors (location-dependent inputs), energy consumption, cost-effectiveness, GREET fuel-cycle emission rate | CNG |
| Ribau et al. (2014) | Oporto (Portugal) | LCA | – | D, FCEV (hybrid and plugin hybrid) | Fuel consumption, CO ₂ | Depends |
| Cooney et al. (2013) | USA | LCA | – | D, BEV | GHGs, particulate formation, ozone depletion, ecotoxicity, acidification impacts | BEV |
| Geng et al. (2013) | Shenyang (China) | IVE | – | D, CNG, HEV-D, BEV | Purchasing cost, fuel cost, maintenance cost, Emissions (VOC, CO ₂ , NO _x , CO ₂ , PM) | CNG |
| Kliucininkas et al. (2012) | Kaunas (Lithuania) | LCIA | – | D, CNG, CBG, BEV (from natural gas; heavy fuel oil) | Fuel consumption, CO ₂ , CO, NO _x , SO ₂ , PM | CBG, E |
| McKenzie and Durango-Cohen (2012) | USA | LCA | – | D, CNG, HEV-D, FCEV | Purchasing cost, Operational cost, GHG | CNG, FCEV |
| Ou et al. (2010) | China | LC | – | D, LPG, CNG, MET, E, DME, FCEV | Energy consumption, GHGs | LPG, CNG, E |
| Ally and Pryor (2007) | Perth (Australia) | LCA | – | D, CNG, FCEV | GHGs, Primary energy demand, air pollutants | FCEV |

(continued on next page)

Table 1 (continued)

| Source | Country of Study | Method | Experts (#) | Bus Type | Indicator | 1° choice |
|-------------------------|----------------------|------------------|-------------|-----------------------|--|-----------------|
| Hellgren (2007) | Sweden | THEPS | – | D, G, HEV, FCEV | Energy consumption | HEV |
| Gerbec et al. (2015) | Ljubljana (Slovenia) | CBA | – | D, CNG, HD | Investment cost, operating cost (fuel, personnel salaries, maintenance), revenues, consumer surplus, travel time savings due to lower congestions, Pollution reduction (GHGs, CO, NO _x , THC, PM ₁₀ , CO ₂ , noise) | CNG |
| Lajunen (2014) | Finland or Undefined | CBA | – | D, BEV, HEV (generic) | Capital costs, Operating costs (energy consumption, maintenance cost), Costs of the energy storage system replacements, Emissions (HC, CO, NO _x , PM) | HEV |
| Gong et al. (2020) | Nanjing (China) | Route test-based | – | BEV (several brands) | Power Consumption, Charging Duration, Daily average driving distance | V8-1-2 V10-2 |
| Keramydas et al. (2018) | Hong Kong | PEMS | – | D, HEV-D | Mean driving and operation conditions, Fuel consumption, Emissions (NO _x , CO, THC, NH ₃ , NO, NO ₂ , N ₂ O, CO _{2e}) | – |

Table 1 is representative, not exhaustive. Studies were chronologically sorted from the most recent to the oldest by method.

(BEV) Battery Electric Vehicles; (D) Diesel; (CBG) Compressed Biogas; (CNG) Compressed Natural Gas; (LPG) Liquefied Petroleum Gas; (MET) Methanol; (HEV) Hydrogen Electric Vehicles; (EEB) Electric with exchangeable batteries; (HEV-D) with diesel fuel; (HEV-CNG) Hybrid electric vehicles with Compressed Natural Gas; (HEV-G) Hybrid electric vehicles with Gasoline (HEV-LPG) Hybrid electric vehicles with Liquefied Petroleum Gas; (HEV-HVO) Hybrid electric vehicles with hydrogenated vegetable oil; (BD) Biodiesel; (G) Gasoline; (HD) Hybrid diesel-hydraulic vehicles; (HVO) Hydrogenated vegetable oil; (HYT) Hythane; (FCEV) Fuel Cell; (DME) Dimethyl ether.

Kahraman, 2014; Hamurcu and Eren, 2020; Ozdagoglu et al., 2022). Nevertheless, few definitions were given to the subjects involved. Actually, some authors do not even define the number of experts consulted (Tzeng et al., 2005; Lanjewar et al., 2015) or the type of expert involved (Büyükoçkan et al., 2018), and who were sometimes referred to as “decision makers” (Vahdani et al., 2011). Furthermore, the number of experts involved appears to have been reduced (i.e., 1–3), probably by virtue of a geographically localized assessment.

In addition, the comparison of bus types could be deemed to be too different among the studies. Though sometimes two to three fuel-alternatives were compared (Ally and Pryor, 2007; Cooney et al., 2013; Lajunen, 2014; Gerbec et al., 2015; Keramydas et al., 2018), generally a wide spectrum of alternatives was considered (e.g., Tzeng et al., 2005; Vahdani et al., 2011; Lanjewar et al., 2015). Certain authors focused on the comparison of brands with the same type of fuel/technologies to determine their performance (Gong et al., 2020; Hamurcu and Eren, 2020; Ozdagoglu et al., 2022). From the LCA approaches emerged a greater specificity of the types of fuel (Ou et al., 2010; Ribau et al., 2014; Graham et al., 2008) or of production (Kliucininkas et al., 2012). The indicators adopted reflected the method applied. MCDM approaches use qualitative (e.g., sense of comfort) and quantitative (e.g., vehicle capacity) indicators that were similar if not equal in Tzeng et al. (2005), Vahdani et al. (2011), Aydın and Kahraman (2014), Lanjewar et al. (2015), and Büyükoçkan et al. (2018). Others differed by subject of comparison. For instance, Hamurcu and Eren (2020) introduced indicators specific to BEVs (e.g., battery capacity, charging time), while Ozdagoglu et al. (2022) introduced technical details to compare multiple brands (e.g., brand reputation/protecting own value in the market). LCA approaches were quite similar as they investigated emission cost indicators (e.g., CO₂, CH₄, N₂O, NO_x, CO, VOC, PM, SO₂) or energy/fuel costs (e.g., fuel consumption). Similarly, CBA approaches thoroughly assessed costs (e.g., investment cost, operating cost) and the resulting environmental benefits.

Finally, results of the first choice showed different outputs, wherein many studies confirmed the CNG buses as the best alternative (e.g., McKenzie and Durango-Cohen, 2012; Geng et al., 2013; Xu et al., 2015), followed by alternatives to E (e.g., Nordelöf et al., 2019) or to EEB (e.g., Cooney et al., 2013; Lanjewar et al., 2015) or HEV (e.g., Lajunen, 2014). Some authors were not able to manage the definition of a unique solution due to its dependence on several conditions, for instance, technological costs that may be reduced over time to make hybrid combustion cell buses better than today’s electric-diesel hybrid buses (Lajunen and

Lipman, 2016). On the other hand, Ribau et al. (2014) found no effective solution that could secure a compromise between cost and fuel consumption. Notwithstanding, the resulting first choices of recent studies selected electric (e.g., Nordelöf et al., 2019) or hybrid alternatives (e.g., Tong et al., 2017). Conversely, studies that are more recent only focused on the comparison of several electric or hybrid brands or models (i.e., Hamurcu and Eren, 2020; Gong et al., 2020; Keramydas et al., 2018).

All these studies have contributed to the application of approaches to evaluate and rank technological alternatives for bus fleets whilst providing valuable results. Regardless, the literature does highlight some possible gaps. First, most of the studies based their evaluation of alternatives on specific geographical and operational features, and on methodologies that might appear to be difficult to reproduce in other situations. Specifically, a clear demonstration of this case was the meagre number of experts involved (i.e., 3, 4 or 7) in the MCDM. Second, the cost analysis appeared to have been overly simplified, specifically in MCDM approaches. Only Gerbec et al. (2015) developed the choice based on a thorough cost-benefit discussion (analysis). Nonetheless, infrastructure related costs were not considered due to the fuel alternatives selected (i.e., D, CNG, HD), as well as the lack/presence of incentives. Moreover, the perspective of PTCs was often not sufficiently highlighted. Either the studies examined did not consider this perspective whatsoever or they considered it only marginally, with a small number of subjects, involved with other types of experts. Therefore, the only choice was to reach a compromise among multiple stakeholders (Tzeng et al., 2005; Aydın and Kahraman, 2014). Third, since existing MCDM-based studies did not integrate AHP, ELECTRE and WSM all in one solution, they did apply to different local/decision-making contexts. Therefore, despite all this high-quality literature, no study has yet proposed an integrated method to evaluate and rank the most promising fuel alternatives, whilst also including a higher number of experts than what can be found in current literature. Consequently, the objective of this study is to address these identified gaps.

3. Methodological framework

The integrated approach has been conceived as a decision-making tool that would aid PTCs in selecting a fuel alternative for a bus fleet. This procedure is organised into three main phases (with seven related steps) according to the scheme illustrated in Fig. 1. These phases and steps are described in what follows.

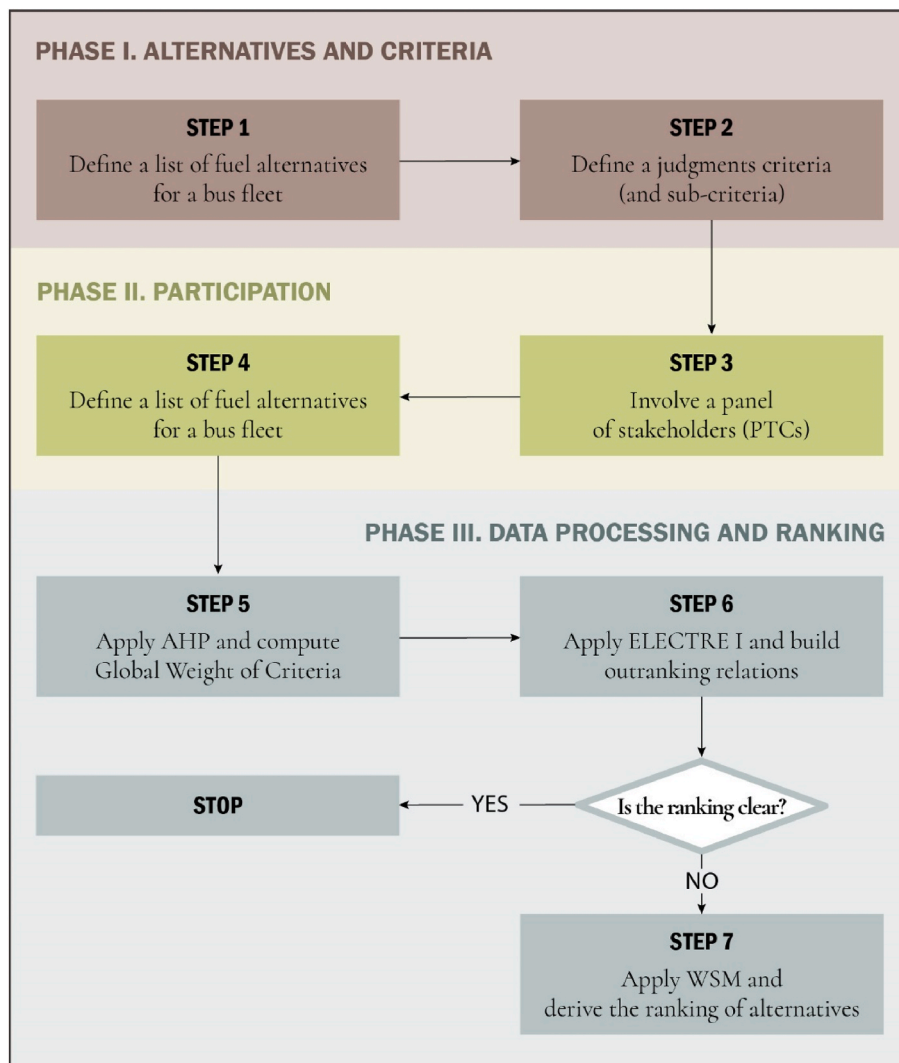


Fig. 1. The flowchart for the proposed integrated method.

In Phase I the different fuels available (i.e., the alternatives) to PTCs and the criteria adopted for their selection are specified. In Phase II, the stakeholders are involved so that their opinions about each criterion at hand can be obtained. In Phase III, the AHP, ELECTRE I, and WSM methods are integrated to provide the best compromise solution (ELECTRE I) and/or the best alternative (WSM).

3.1. Phase I - alternatives and criteria

Phase I sets some preliminary tasks to frame the different kinds of fuels (i.e., alternatives) that might be relevant for PTCs and the judgement criteria according to step 1) and step 2) respectively, to perform the MCDM. Step 1) aims to define fuel alternatives to be considered, which represent those available to the PTCs' managers. In this study, these alternatives are finite in number and predetermined. Step 2) seeks to judge each alternative against each criterion. Indeed, each MCDM decision problem is associated with a multiplicity of 'objectives', or 'criteria' representing the different viewpoints from which each alternative can be observed and, thus, judged. Usually, these criteria are conflicting, considering that the improvement of performance for one criterion could be worse for another.

If this was not the case, the MCDM problem would have a simple solution, since it would be possible to directly identify the formula that would best meet all the criteria, among those available. Nevertheless,

the MCDM method makes it possible to evaluate the best compromise solution because it manifests the best overall response to a set of criteria. Therefore, Step 2) strives to hierarchize the problem: once the objective has been fixed, the problem should be split into criteria and sub-criteria and sub-sub-criteria, where appropriate, which are chosen according to the research objective. It is worth noting that, while all criteria are general, each one may have a distinct level of significance as it can vary to represent different perspectives.

3.2. Phase II - Participation

In Phase II, a panel of stakeholders is identified, and their opinions about criteria and sub-criteria are gathered; it runs according to steps 3) and 4), respectively. Unless specified otherwise, both criteria and sub-criteria will be referred to as criteria in the subsequent text. Determining the importance of criteria is not a trivial task because specific knowledge is required. Therefore, the engagement of experts in the perceived evaluation of criteria is a crucial task, which characterises Step 3). PTC managers are here considered 'experts' because they can offer daily-operational judgement from a managerial viewpoint. The involvement of experts is highly recommended because their diverse opinions may result in multiple evaluations of the criteria. Since these opinions can differ due to the specific knowledge of the criteria, and consequently, provide different perspectives, a weighing process is

essential to determine the relative importance. This process is also necessary in the application of MCDM. Hence, importance weighting was attached to the criteria. While weights can be attached by querying experts for preferences on individual items, this approach may be flawed because humans often struggle to process relevant information about all criteria, especially when many are being evaluated at one time (e.g., Carrara et al., 2021; Carra et al., 2022). Numerous authors have suggested diverse approaches to weighting the items (e.g., Hens and De Wit, 2003; Wang and Lee, 2009). Nonetheless, since the MCDA method is applied in this study, it is also used to the weighing process. Among the different methods, this study utilises the AHP due to its effectiveness in mitigating potential bias risks (Saaty, 1987, 1994). This method helps in modelling scenarios involving uncertainty and risk by enabling the derivation and combinational of multidimensional scales into a unified priority scale (Wind and Saaty, 1980; Figueira et al., 2005). Moreover, the AHP provides those mathematical foundations (e.g., eigenvectors) that establish weights from each judgement to achieve an objective evaluation.

Although experts can be involved in several ways, this study adopted a survey that permitted the involvement of the largest number of interested experts to be contacted according to Step 4). In reflecting on the kind of canvass to be used, a web survey was selected owing to its several advantages and its application in many other fields (Carra et al., 2023). Specifically, the web survey can: 1) rapidly reach experts, 2) elicit information at a low cost, 3) be compiled directly online, 4) provide data that are ready to be processed just as they are found when received, and 5) be one of the few possible applicable tools during the Covid-19 pandemic (the period of study). While opting for a traditional e-mail survey could have been a compelling choice, since the experts contacted could save the file, print it, and/or may not necessarily need to be online to respond, a closer assessment of the previous advantages suggested adopting the web survey format.

3.3. Phase III - data processing and ranking

In Phase III, the collected data from the experts was processed by applying AHP in step 5), ELECTRE 1 and in step 6), and, finally, WSM in step 7) as described below and similarly to Carra et al. (2023).

3.3.1. Applying AHP

In Step 5), the processed data resulted by the AHP included stable weight assignment for pairwise comparisons of criteria. Furthermore, in order to mitigate potential biases in the decision-making process, the AHP established a ratio scale for each group of pairwise comparisons to assess the consistency or inconsistency of the judgements provided. In achieving this, the AHP employed raised subjective comparisons on a pair of criteria and then aggregated those outcomes into weights, addressing the greater or lesser subjectivity of the expert engaged. Indeed, the method was capable of grappling with conflicts or disagreements among groups with potentially conflicting goals or positions. Outcomes from the AHP proved significant output considering the diverse aspects and numerous measurements that characterised the criteria for bus fleet evaluation.

In particular, a matrix of pairwise comparisons was built for each expert. Rows and columns of the matrix show criteria. Each entry had a weight assigned to one criterion with respect to another. Next, a vector of weights for each criterion was initially computed and subsequently normalised. Afterwards, inconsistencies in the judgments became evident. Therefore, a consistency test was conducted to validate the reliability of the judgments within each matrix. Formally, let J be the set of criteria (or sub-criterion), K be the set of experts, v_j/v_h be the numerical judgment of the pairwise comparison between criterion $j \in J$ and $h \in J$, respectively. Subsequently, let V_j be the overall un-normalised weight of criterion $j \in J$, and CI denote the consistency index. The CI assesses whether the judgments provided by expert $k \in K$ are logical and consistent with the choices reported in the survey. Next, let λ_{max} be the

maximum eigenvalue required for computing the measure of consistency, and RI be the random consistency index, a CI function tabulated based on the maximum number of items. Finally, a four-step algorithm was then employed to compute the weights and perform the consistency check of the judgments.

For every expert $k \in K$:

1. Construct the matrix of pairwise comparison V^k among criteria for each expert $k \in K$.
2. Compute V_j and v_j from this matrix. Specifically, the computation of the weight vector V_j is performed as follows:

$$V_j = \sqrt[j]{\prod_{h \in J} v_{jh}} \quad \forall j \in J \tag{1}$$

Next, V_j is normalised using the average arithmetic method as follows:

$$v_j = \frac{V_j}{\sum_{h \in J} v_h} \quad \forall j \in J \tag{2}$$

3. Check the consistency.

Compute λ_{max} as follows:

$$\lambda_{max} = \frac{\sum_{j \in J} \left[\frac{\sum_{h \in J} \left(\frac{v_{jh}}{v_h} v_j \right)}{v_j} \right]}{|J|} \tag{3}$$

Verify $\lambda_{max} \geq |J|$.

Compute CI as follows:

$$CI = \frac{(\lambda_{max} - |J|)}{(|J| - 1)} \tag{4}$$

The assessments exhibit perfect consistency if $\lambda_{max} = |J|$, thus $CI = 0$.

Finally, the consistency ratio is computed as follows:

$$CR = \frac{CI}{RI} \tag{5}$$

where RI is predefined table number, based on the number of criteria (j) considered, obtainable from, e.g., Saaty (1987).

The pairwise comparisons were considered consistent when Consistency Ratio (CR) < 0.1 (10%). Alternatively, experts might be engaged once more to reassess their evaluations. More details of the application of AHP are provided in Saaty (1987, 1994). It is worth noting that different matrices were assembled for criteria, sub-criteria and sub-sub-criteria, for each expert $k \in K$. Moreover, experts who did not adhere to the consistency constraint were discarded; only consistent judgments were considered in the weightings process. Moreover, the weightings computed for each 'consistent' expert were averaged to obtain the final weights. These were called Global Weights and were derived for each criterion and sub-criterion, at the end of Step 5). Global Weights were employed as inputs for the decision matrix, as shown in the next steps.

3.3.2. Building the decision matrix and applying ELECTRE I

In Step 6), the ELECTRE I preference aggregation method is implemented to facilitate the identification of a compromise solution among alternatives (and in some cases also the best one). ELECTRE I initiates by building a decision matrix. Each row of this matrix represents the alternative, whereas each column has the criterion at hand. Each entry indicates the performance of the generic alternative with respect to the generic criterion. Once the decision matrix has been built, each criterion is categorised as either a benefit or a cost. For instance, a higher value of

vehicle lifecycle indicates a more favourable the alternative: therefore, the lifecycle of the vehicle is regarded as a benefit. Conversely, a higher purchase price for the bus indicates a less favourable alternative: in this case, the purchase price is considered a cost. Next, the decision matrix is converted into a new matrix by utility functions, with the assumption of linearity in this research. Specifically, each utility function was constructed for each criterion according to the initial value assigned to each alternative. This function ranged from a maximum value, i.e., 1 to a minimum value, i.e., 0 according to the criterion at hand. If the criterion represented a benefit, the utility function had a minimum value of 0 and a maximum value of 1. A reverse interpretation was given when the criterion was a cost: the maximum value was attributed to alternatives that had the lowest cost. Once these extremes were fixed, the intermediate values were computed by a linear interpolation of the value indicated for each alternative, according to the criterion considered.

Formally, once computing the weights v_j of criteria $j \in J$, the method can be expressed as follows. Let: I be the set of alternatives and $i \in I$ a single alternative. Let F be the set of performances for $i \in I$ in relation to $j \in J$, and let f_{ij} be an individual performance. Then, let V be the set of weightings, with $v_j \in V$ denoting the normalised weight of criterion $j \in J$. Similarly, U be the set of utilities, and $u_{ij} \in U$ an individual utility for $i \in I$ concerning $j \in J$.

The method sought the optimal solution $I^* \subset I$, defined as that one demonstrating the highest overall compliance with criterion $j \in J$ by assigning suitable weights to each criterion.

The utility matrix was built using the utility function, replacing individual performance ($f_{ij} \in F$), derived from the decision matrix.

Next, the method builds one or more outranking relations, allowing for a comprehensive comparison of every possible pair of alternatives or options. Specifically, it necessitates computing concordance and discordance indexes to implement an ‘elimination’ process, wherein less ‘satisfactory’ alternatives are excluded, leaving those that serve as a favourable compromise to achieve the final objective. The concordance index (I_c) be the summation of normalised weights $v_j \in V$ (resulted from the AHP) of criterion $j \in J$, constituting the coalition of criteria where alternative $i \in I$ is preferable to $g \in I$. The discordance index (I_d) be the maximum value of the greater difference in utility for each criterion $j \in J$, favouring alternative $g \in I$ over $i \in I$. I_c and I_d reflect the degree of satisfaction/dissatisfaction in selecting one alternative over another. These indexes are computed as follows.

I_c : for each pair of alternatives $i \in I$ and $g \in I$, and for each criterion $j \in J$,

select u_{ij} and u_{gj}
 If $u_{ij} \geq u_{gj}$ then select v_{ij} ; else, select v_{gj} ;
 next calculate

$$I_{c_{ig}} = \sum_{j \in J} v_{ij} \quad \forall i, g \in I \quad (6)$$

$$I_{c_{gi}} = \sum_{j \in J} v_{gj} \quad \forall i, g \in I \quad (7)$$

I_d : for each pair of alternatives $i \in I$ and $g \in I$, and for each criterion $j \in J$,

select u_{ij} and u_{gj}
 If $u_{gj} \geq u_{ij}$ then calculate

$$\Delta u_{gj} = (u_{gj} - u_{ij}) \quad (8)$$

$$\Delta u_{maxj} = Umax_j - Umin_j \quad (9)$$

$$R_{gj} = \frac{\Delta u_{gj}}{\Delta u_{maxj}} \quad (10)$$

$$I_{d_{gi}} = Max (R_{gj}) \quad (11)$$

else calculate

$$\Delta u_{ij} = (u_{ij} - u_{gi}) \quad (12)$$

$$\Delta u_{maxj} = Umax_j - Umin_j \quad (13)$$

$$R_{ij} = \frac{\Delta u_{ij}}{\Delta u_{maxj}} \quad (14)$$

$$I_{d_{ij}} = Max (R_{ij}) \quad (15)$$

Next, the selection of the best compromise solution involves utilising the joint outranking relationship of I_c and I_d , respectively. In particular, for each pair of alternatives, $i \in I$ is considered preferable to $g \in I$ if $I_{c_{ig}}$ is close to 1. Conversely, $g \in I$ is deemed preferable to $i \in I$ if $I_{d_{gi}}$ is close to 1. Nonetheless, to acquire information in the same direction, we can contend that $i \in I$ is considered preferable to $g \in I$ if $I_{c_{ig}}$ is close to 1 and $I_{d_{ig}}$ is close to 0. To perform the selection among alternatives, the method needs to establish a pair of threshold values for I_c and I_d . These thresholds are defined by \underline{I}_c and \underline{I}_d , respectively. These limit values allow for the exclusion of all pairs of alternatives that do not fit within the specified interval. Specifically, alternatives $i \in I$ and $g \in I$ are retained if $I_{c_{ig}} > \underline{I}_c$ and $I_{d_{ig}} < \underline{I}_d$. Contrary, the opposite condition is not hold. Nevertheless, it could result that alternative $i \in I$ is favoured over $g \in I$ for the concordance index, while alternative $g \in I$ might be favoured to $i \in I$ for the discordance index. In this case, it is not feasible to define an outranking. Moreover, the drawback of these indexes lies in the necessity to define threshold values. To address the relatively arbitrary thresholds selection, the global concordance (\widehat{I}_c), and discordance (\widehat{I}_d) indexes were adopted. Specifically,

$$\widehat{I}_c = \sum_{j \in J} I_{c_{ig,j}} - \sum_{j \in J} I_{c_{gi,j}} \quad \forall i, g \in I \quad (16)$$

$$\widehat{I}_d = \sum_{j \in J} I_{d_{ig,j}} - \sum_{j \in J} I_{d_{gi,j}} \quad \forall i, g \in I \quad (17)$$

A higher value for \widehat{I}_c and a lower value for \widehat{I}_d indicate a more favourable alternative. Therefore, alternatives with a positive \widehat{I}_d and a negative \widehat{I}_c were excluded from the ranking.

3.3.3. Applying WSM

Often, ELECTRE I does not provide sufficient findings to identify the ‘best’ alternative. Therefore, other evaluation methods are required to obtain (refine) a ranking among alternatives. Of these, the WSM is probably the most frequently used, owing to its straightforward computation. The method assumes an additive utility: i.e., the overall value of each alternative is equal to the sum of its performance, appropriately weighted, with respect to all criteria. The WSM works as follows. First, the utility indices of the decision matrix are transformed from absolute to relative indices (i.e., they are normalised to the total column) as follows:

$$\bar{u}_{ij} = \frac{u_{ij}}{\sum_{i \in I} u_{ij}} \quad \forall j \in J \quad (18)$$

Next, an aggregate score (denoted by S_i) is computed for each alternative $i \in I$ as follows:

$$S_i = \sum_{j \in J} w_j \bar{u}_{ij} \quad \forall i \in I \quad (19)$$

Next, the ‘best’ alternative $i \in I$ has the maximum (or the minimum) value of S_i , depending on whether the objective of the decision maker is to maximise (e.g., profits, benefits in general; i.e., benefit criteria) or to minimise the value of the performance f_{ij} (e.g., costs to be incurred to perform a certain action, disadvantages in general).

4. Application to the Italian case

The proposed approach was implemented in the Italian context to assess the outcomes, consistency of the method, and to draw reflections on the relative importance of various components that could impact the future policies of the PTCs.

4.1. Phase I: defining alternatives and judgement criteria

According to Step 1) and Step 2) of Phase I, fuel alternatives and criteria representing common facets of available fuels were specified. On the one hand, many fuels can be considered. Our analysis included: (a) Battery Electric Vehicles (BEV), (b) Fuel Cell Electric Vehicles (FCEV), (c) Diesel (D), (d) Compressed Natural Gas (CNG), (e) Liquefied Natural Gas (LNG), and (f) Hybrid Electric Vehicles (HEV). These alternatives represented the vehicles currently on the market or that are emerging according to European directives and policies under the Green Deal. On the other hand, the literature suggested several criteria (or indicators) for the analysis of fuel alternatives. In this study, three ‘main’ criteria were being considered. These included: (A) environmental impact, (B) vehicle lifecycle, and (C) costs. These are referred to as Level 1 criteria.

As for (A), we focused on CO₂ emissions, a commonly studied criterion (e.g., Keramydas et al., 2018; Graham et al., 2008; Ribau et al., 2014), and measured in gCO₂/km in what follows. As for (B), the impact from production to vehicle disposal has been considered since suggested by several authors (e.g., Tong et al., 2017; Aydin and Kahraman, 2014). Moreover, this criterion allows PTCs for a more consistent comparison of input data since these can be standardised over the vehicle lifecycle. The vehicle lifecycle was measured in years. Regarding costs (C), the study expanded sub-criteria such as purchasing, operational, and maintenance costs as suggested by the literature review (e.g., Büyükoçkan et al., 2018; Lanjewar et al., 2015), aiming for a more detailed examination. More precisely, costs, being the most relevant criteria for PTCs, were divided into sub-criteria such as: (C₁) purchasing and (C₂) operating costs. The concept of purchasing and operating costs can be very broad and connected to the compatibility between the development of economic activities and environmental protection. Hence, specific sub-criteria for C₁ and C₂ were considered, respectively. Precisely, purchasing cost was organised into (C₁₋₁) Bus purchase and (C₁₋₂) infrastructure. Operating cost was divided into (C₂₋₁) Bus maintenance, (C₂₋₂) Fuel price, (C₂₋₃) Battery change, (C₂₋₄) Cylinder testing, (C₂₋₅) infrastructure maintenance, and (C₂₋₆) Energy infrastructure cost. All these sub-criteria were referred to as Level 2 criteria. It is worth noting that, to consider the economic advantage of the specific type of fuel over the entire period of use, the criteria of the cost matrix were calculated according to (i) the lifecycle of the different types of traction, (ii) the mileage, (iii) the number of buses in the fleet, and (iv) the number of refuelling points required for the various types of traction.

4.2. Phase II: the survey

Following steps 3) and 4), a web-based survey involving experts was conducted to gather their judgements. The choice of experts took into account the national scale of the study and the multiple perspectives on the topic. Consequently, the experts selected were Italian PTC managers,

thus ensuring the authenticity and reliability of their responses to real-life issues. Involving only PTC managers as experts ensures a focused exploration of practical implementation of renewable energy in public transit systems, leveraging their industry expertise, specialised knowledge, and experiences as industry practitioners directly involved in transit operations. Moreover, the inclusion of solely PTCs, both public and, notably, private, allows for (i) the aggregation of data specifically related to one sector and (ii) a focus on identifying the factors that may encourage or deter PTCs from augmenting their bus fleets with alternative fuels.

PTCs’ managers were identified through the Google and LinkedIn search engines and subsequently sampled randomly. A total of 91 PTCs were involved. The survey was created using the Qualtrics XM platform, and participants provided responses anonymously.

A distinction was made between urban and interurban vehicles and hence different types of traction, given their limitations in terms of mileage. Specifically, it was considered useful to carry out a kind of market survey to assess the approach of PTCs towards new technological fuel alternatives. The survey was organised into two sections. The first section regarded (i) preferences between investments in emerging or current fuel alternatives, and (ii) rankings of fuel alternative preferences for urban and interurban services. Moreover, these services were distinguished in the next part of the method. The second section considered pairwise comparisons among criteria and related sub-criteria, wherein the experts assessed which one was more relevant and how much more relevant it was (e.g., twice as much). Nonetheless, the experts were required to evaluate each criterion using an adjusted version of Saaty’s Semantic Scale, ranging from 1 to 5 points (Table 2). The choice of a 5-point scale was provided for to avoid a response spread of values among the respondents.

Questions were asked as follows. First, respondents judged which criterion was more relevant and to what extent among those of level 1 (lifecycle, costs, environment). Then, they were asked to compare the nested items of level 2. Note that purchasing and operating costs were not compared, because the criteria were assumed to be of equal relevance. An example of a part of the second section of the survey is shown in Fig. 2.

Notably, the responses from the PTCs that adopted urban, interurban, or both services varied significantly as their evaluation criteria differed quite a bit, given the different distances covered and the diversity of some of their costs. For those PTCs that adopted both services, the weightings were considered as an aggregate, assuming that respondents considered their case in a manner that was as generalised as possible. It is likely that their considerations were little diversified, owing to their dependence on hunches and their accumulated experience.

4.3. Phase III: data processing and results

The survey, which ran in a wave of data collection from March to April 2020, was completed by 30 different PTCs (a response rate = 30/91), of which 6/30 were operated by urban services, 5/30 by interurban services, whilst the majority, or 19/30 were operated by both services. Surprisingly, when looking at the data from the first section, 13/30 of the PTCs preferred to invest in established fuel alternatives, and 17/30

Table 2
The adjusted AHP rating scale.

| Intensity | Judgement | Explanation |
|-----------|--------------------|---|
| 1 | Same importance | Two criteria contribute equally to the objective |
| 2 | Low importance | Intermediate situation between 1 and 3 |
| 3 | Medium Importance | Experience and judgements slightly lean towards one criterion over the other. |
| 4 | More than moderate | Intermediate situation between 3 and 5 |
| 5 | Strong importance | One criterion is significantly favoured over the other |

| Question 1 | | <i>Which of the following aspects are more relevant in your operational plan and in that extent? Please, consider, for example, that a "5-point" for Life cycle implies that this criterion is five times more important than the other option.</i> | | | | | | | | | |
|-------------------|-----------------------|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------|--|
| Criterion | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | Criterion | |
| Cost | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Environment | |
| Environment | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Life cycle | |
| Life cycle | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Cost | |

| Question 2 | | <i>In relation with investment costs for bus purchasing, which aspect is more relevant and in what extent? Please, consider, for example, that a "5-point" for bus purchase implies that this sub-criterion is five times more important than the other option.</i> | | | | | | | | | |
|----------------------|-----------------------|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|----------------------------|--|
| Sub-Criterion | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | Sub-Criterion | |
| Bus purchase | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Fuel price | |
| Bus maintenance | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Bus purchase | |
| Bus purchase | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | Energy infrastructure cost | |
| ... | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | ... | |

Fig. 2. Example of the questionnaire for pairwise comparisons of criteria and sub-criteria.

in innovative alternatives, only when government incentives were offered, whilst the remainder preferred innovative fuel alternatives regardless of whether or not any incentives were a part of the solution. In addition, most PTCs operating urban and interurban services showed a preference for investment in D, whereas they seemed to ‘discard’ the HEV option. Although this latter result could be viewed as unexpected, it might be justified owing to this technology’s scarce diffusion as well as the total absence of defined regulation in Italy.

4.3.1. Applying AHP

In Step 5), the AHP was applied. The weights of each item were computed according to eqns. (1) and (2). Two matrices were implemented, for the criteria in levels 1 and 2, respectively. The consistency of responses was assessed for each of the PTCs according to eqns. (3)–(5). The weights were then stated in an aggregate manner owing to the low number of experts interviewed. Final weights were derived by averaging the criteria weights obtained for each of the PTCs. In this way, this phase was concluded by computing the Global Weights, which are shown in Tables 3 and 4, respectively. All these tables are self-explanatory. The weights show the differences obtained from the experts’ opinions concerning the criteria investigated and the type of service. Table 3 shows that experts gave a higher priority to the criteria of Cost, Lifecycle, and Environment both in the case of urban and interurban services. Table 4 shows that experts gave a relative priority to the Bus Purchase criterion in both urban and interurban services. This result reveals that PTC managers slightly deemed investments in vehicles more relevant instead of infrastructure, perhaps because traditional vehicles that were also being adopted required less investment than new infrastructure. Thus, PTC managers thought that the vehicles would cost more than the

Table 3
Weights matrix for criteria of level 1.

| Type of Service | Environment (A) | Lifecycle (B) | Cost (C) |
|-----------------|-----------------|---------------|----------|
| Urban | 0.23 | 0.32 | 0.45 |
| Interurban | 0.21 | 0.37 | 0.42 |

Table 4
Weights matrix for criteria of level 2.

| Type of Service | Bus purchase | Infrastructure investment | Bus maintenance | Fuel price | Battery change | Cylinder testing cost | Infrastructure maintenance | Energy infrastructure cost |
|-----------------|------------------|---------------------------|------------------|------------------|------------------|-----------------------|----------------------------|----------------------------|
| | C ₁₋₁ | C ₁₋₂ | C ₂₋₁ | C ₂₋₂ | C ₂₋₃ | C ₂₋₄ | C ₂₋₅ | C ₂₋₆ |
| Urban | 0.14 | 0.11 | 0.14 | 0.14 | 0.19 | 0.12 | 0.08 | 0.08 |
| Interurban | 0.15 | 0.11 | 0.13 | 0.13 | 0.20 | 0.11 | 0.09 | 0.09 |

infrastructure. Furthermore, experts accorded a high priority to battery replacement for both urban and interurban services. These findings were unexpected as they might have been considered part of routine bus maintenance. Nevertheless, no relevant differences were noted in the case of PTCs that operated both urban and interurban services.

4.3.2. Costs, lifecycle, and emission estimations

Once the criterion weights were obtained, the costs (purchase and operation) lifecycle and emission estimations were calculated for each alternative. Specifically, the costs for each alternative were evaluated both through an examination of recent literature and/or using current market prices, as well as through direct assessments advanced by service providers thanks to manufacturers’ interviews. Moreover, the lifecycle for each alternative was also estimated from interview questionnaires submitted to the PTCs. Finally, environmental impact was estimated by the emission values defined using the industry database for each kind of technology (ISPRA, 2015; Mobility Innovation Tour, 2020; European Union, 2021).

Table 5 shows the costs for bus purchase and investment in infrastructure for each alternative. Notably, the purchase costs are only indicative because they would vary according to the size of the fleet, each of the PTCs’ needs, and the funding that any PCT was able to acquire.

In the case of LNG and L-CNG plants, the plant suppliers typically enable the provision of the fuel, with the solution of the infrastructure being provided on a loan-for-use basis. This way, the selling price of natural gas would include the cost of the raw material, tolls, and fees for third-party access to gas facilities, rental of strategic reserves, loan of the refuelling plant, maintenance of the plant installed at the customer’s premises, other supplier management and operating costs, and costs for transport from the gasifiers to the customer’s plant. Therefore, because purchase and maintenance costs were not included in the package, the fuel cost was higher.

Based on the values provided by one of the main LNG plant suppliers in Italy, Table 6 shows the fuel prices adopted in our method. Moreover, statutory taxes and duties should also be added to the above LNG prices:

Table 5
Bus purchasing and infrastructure investment costs.

| Fuel alternative | Bus purchasing costs | | | | Infrastructure investment costs | |
|------------------|-----------------------------------|-------------------|----------------------|-------------------|---|--------------------|
| | Urban | | Interurban | | Description | Value [k€] |
| | Without funding [k€] ^a | With funding [k€] | Without funding [k€] | With funding [k€] | | |
| BEV | 450 | 90 | – | – | For each pantograph (300 kW) For each charging station at the depot (100 kW) | 275 30 |
| Mild HEV | 280 | 280 | 255 | 255 | – | – |
| HEV | 380 | 380 | 345 | 345 | – | – |
| Diesel | 220 | 220 | 200 | 100 | – | – |
| CNG | 250 | 100 | 230 | 46 | Slow charge (starting pressure 20 bar) with 20 filling posts, one compressor working and one reserve* Fast charging (starting pressure 20 bar) with 2 working compressors and one reserve compressor and 2 double dispensers (*) | 370** 530 (**) |
| LNG | – | – | 260 | 52 | 80 m ³ storage tank, 10 bus/h refuelling and 2 LNG dual dispensers | 1000 (**) |
| FCEV | 850 | 850 | – | – | For each charging station at the depot (100 kW) H ₂ production and refuelling plant For each charging station at the depot (350 bar) | 3500 7200 25 |

*Plant for refuelling 20 buses in 8 h; ** Including construction works (assembly, testing and charging station); (*) Plant for refuelling 20 buses in 3 h; (**) Including construction works (assembly, testing and shelters).

^a The purchase costs of urban and interurban vehicles have been evaluated by including the funding program of the Italian state defined by the National Strategic Plan for Sustainable Mobility (PSNMS) and European one according to the following percentages. Indeed, the Italian State co-funds the buses' purchase by PSNMS for (a) BEV (80% in urban area); (c) D (50% in interurban area) and (d) CNG (60% in urban area and 80% for interurban) and (e) LNG (60% in urban area and 80% for interurban). Conversely, European co-funds the purchase of (b) hydrogen.

Table 6
Variation in LNG-C and LNG cost for plants on loan for use.

| Baseline quantity | LNG-C ^a | | LNG | |
|-------------------|--------------------|---------------|--------------|---------------|
| | €/kg 8 years | €/kg 10 years | €/kg 8 years | €/kg 10 years |
| kg year | | | | |
| 1,400,000 | 0.589 | 0.560 | 0.627 | 0.591 |
| 1,600,000 | 0.570 | 0.545 | 0.603 | 0.571 |
| 1,800,000 | 0.555 | 0.533 | 0.585 | 0.557 |
| 2,000,000 | 0.543 | 0.523 | 0.570 | 0.545 |

^a LNG-C from LNG regasification.

(i) excise duty to be applied to motor vehicles and equal to 0.0042 €/kg (current value) and (ii) cylinder fund (applies only to the portion of methane sold as CNG, equal to 0.0379 €/kg). In addition, as seen for FCEVs, funding obtained by PTCs that experimented with this power supply was considered in our calculations.

As far as the vehicle maintenance costs are concerned, only ordinary maintenance was considered, since costs for extraordinary maintenance could not be assessed or estimated. These figures are listed in Table 7 together with the infrastructure maintenance costs.

Fuel cost was evaluated according to the consumption and fuel price so that comparable units of measure [u.m.], for both urban and interurban services could be obtained. BEV and FCEV alternatives require a battery change every 5 years for a total of €40k per vehicle, whereas CNG¹ requires a cylinder change for a total of €1k per vehicle every 4 years, both of which increased operating costs. Results are shown in Table 8, including energy infrastructure costs.

Once all the cost data were collected, a single matrix that would link each alternative to Level 1 criteria for environment, lifecycle, and costs as well as Level 2 criteria for costs was constructed. To consider the

¹ Moreover, CNG buses require cylinder testing every 4 years, pursuant to the R110 European standard. The overhaul consists of four checks: (i) weighing; (ii) visual inspection; (iii) ultrasound testing; (iv) pressure test. Failure to pass even one of the above checks requires the cylinder to be scrapped. Cylinder testing is free of charge. PTCs need only bear the costs of personnel to assemble and disassemble the cylinders, as well as for transport to the company that manages them. If the test fails, the cylinders are replaced free of charge, since the same PTCs that carry out the testing and replacement will receive the contribution of the excise tax on the cylinders.

economic advantage of the specific type of traction power supply over the entire lifecycle of each solution, the cost items in the matrix were calculated according to baseline hypotheses even for urban and interurban vehicles defined in Table 9.

Notably, when considering BEVs, assuming that each bus is equipped with a 350-kWh battery, each vehicle can be fully recharged in 3.5 h at a 100-kWh column. Therefore, the number of columns assumed for the BEV buses was set at the same number of vehicles in the fleet so that all vehicles could be recharged quickly. To include recharging via pantograph in the analysis, it was assumed that there was just one single pantograph for the entire route, giving the company to vary the number according to its own needs. The number of dispensers for refuelling CNG buses would range according to whether the plant offers slow- or fast-filling. The following was assumed for the slow-fill plants where refuelling takes 8 h, with the infrastructure made up of 20 recharging points. Buses can be operational after 3 h, owing to the presence of 2 double dispensers in the fast-filling plants. If LNG was used, 2 double dispensers were assumed for the refuelling of 10 buses/h. Then, the value of four was assumed as the number of refuelling columns necessary for the FCEV fleet, starting from a recharge time of 20 min per bus. This way, 4 buses could be recharged at one time, thus, coming to 12 buses per hour. Therefore, in less than 2 h it would be possible to recharge the entire fleet (assuming that the fleet is made up of 20 buses). These hypotheses could always be updated in the future in view of the fact that technological evolution is pushing toward the abandonment of the old steel tanks to be replaced by tanks made of new composite materials, which are more resistant and suitable for high pressure storage.

Table 7
Maintenance bus and infrastructure costs for each alternative.

| Fuel alternative | Bus maintenance | | Infrastructure maintenance | | |
|------------------|-------------------|-------------------|---|-------------------------|-------------------|
| | Urban [€/km] | Interurban [€/km] | Description | Value | [u.m] |
| BEV | 0.20 | – | For each column (100 kW) Pantograph (300 kW) | 3000 27 ^a | €/2years €/day |
| Mild HEV | 0.18 | 0.14 | – | – | – |
| HEV | 0.22 | 0.17 | – | – | – |
| Diesel | 0.24 | 0.19 | – | – | – |
| CNG | 0.25 | 0.2 | CNG production plant | 0.057 | €/kg |
| LNG | – | 0.2 | LNG production plant | 0.005 | €/kg |
| FCEV | 0.89 ^a | – | H ₂ production plant | 300 ^a | €/year |
| | | | Recharge station at depot (350 bar) | 0.057 | €/kg |

^a Including the cost of changing fuel cells.

Table 8
Aggregated fuel cost for each alternative for urban and interurban services.

| Fuel alternative | Bus fuel cost | | | | Energetic infrastructure costs | | | |
|------------------|---------------|---------------|--|-------------|--------------------------------|---|------------------|----------------|
| | Consumption | [u.m] | Fuel cost | [u.m] | Aggregate fuel cost [€/km] | Description | Value | [u.m] |
| BEV | 1.4 | kWh/km | 0.15 | €/kWh | 0.21 | For each column (100 kW) Pantograph (300 kW) | 0.015 0.015 | €/kWh €/kWh |
| HEV/Mild HEV | 2.1 (2.4) | km/l (km/l) | 0.97 ^a (0.97 ^b) | €/l (€/l) | 0.46 (0.40) | – | – | – |
| Diesel | 2.2 (2.5) | km/l (km/l) | 0.97 ^a (0.97 ^b) | €/l (€/l) | 0.44 (0.39) | – | – | – |
| CNG | 2.7 (3.2) | km/kg (km/kg) | 0.33 ^b (0.33 ^b) | €/kg (€/kg) | 0.12 (0.10) | CNG production plant | 0.057 | €/kg |
| LNG | (3.2) | (km/kg) | (0.64 ^c) | (€/kg) | (0.19) | LNG production plant | 0.005 | €/kg |
| FCEV | 0.08 | kg/km | 11.30 | €/kg | 0.90 | H ₂ production plant | 300 ^a | €/year |
| | | | | | | Recharge station at depot (350 bar) | 0.057 | €/kg |

^a Including the recovery of excise duty of 0.214 €/L.

^b Including the excise duty of 0.0042 €/kg and the cylinder fund of 0.0379 €/kg (current year).

^c Including the excise duty of 0.0042 €/kg applicable to road transport.

Table 9
Examples of starting hypotheses for the numerical case.

| Hypothesis | Urban | Interurban |
|---|--------------------------------|---------------------------|
| Vehicle n. | 20 | 20 |
| km/year | 30,000 | 40,000 |
| Number of charging stations (BEV) | 20 | – |
| Number of pantographs and columns (BEV) | Pantograph Columns | 1 – |
| Number of filling stations (CNG) | Slow recharge Fast recharge | Fast recharge 2 double |
| Number of filling stations (LNG) | – | 2 double |
| Number of filling stations (FCEV) | 4 | – |

4.3.3. ELECTRE I results

Once the environmental impact and vehicle lifecycle costs were estimated, a decision matrix was constructed. Next, the concordance and discordance indexes were computed to find the best compromise solutions among all the alternatives. Since a single decision matrix was adopted for urban services (Table 10) and interurban services (Table 11), the cost values inserted into the decision matrix were intended to be averages calculated from those provided by interviews of the PTCs.

These average values were used to simplify the description of the overall method for both urban and interurban services. Notably, purchasing costs for each alternative in Tables 13 and 14 were considered for a regime ‘with funding’. However, the article does not include them due to space constraints, even though they were computed for a scenario ‘without funding’.

For both services, each column was evaluated as a cost or a benefit. The criteria in euro were taken as costs whilst the polluting emissions as benefits (in the hypothesis that by reducing the emissions the environmental benefit would be increased). The criteria relating to the lifecycle of a bus were also deemed benefits. The matrices were normalised by utility functions defined in section 3.3.2, and by eqns. from (6) to (15),

whilst the concordance and discordance tables were built to carry out pairwise comparisons among the alternatives. Next, the concordance and discordance global indices were determined by applying eqns. (16) and (17), respectively.

The results are shown in Tables 12 and 13 for urban and interurban services. These considerations take into account whether funding is available or not (fuel alternatives with invalid values of $\hat{I}c_i$ and $\hat{I}d_i$ were excluded from these tables). The data clearly indicate that funding plays a significant role as the ‘ranking’ differs, even though a distinct rank was not obtained. For instance, in the case of interurban services, alternative HEV Mild was preferred over LNG with production plant (on loan) according to the global concordance index. Conversely according to the global discordance index the opposite also held true.

4.3.4. Weighted sum method

Finally, the WSM index was used to obtain the ranking of all the possible alternatives. The results (with and without funding) are shown in Tables 14 and 15 and sorted in descending order, for both urban and interurban services.

Table 10
Decision Matrix for urban services.

| Weights of Criterion ^a | 0.32 | 0.23 | 0.063 | 0.048 | 0.073 | 0.065 | 0.092 | 0.049 | 0.031 | 0.027 |
|--|-----------|--------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Fuel alternatives | A [years] | B [gCO ₂ /km] | C ₁₋₁ [k€] | C ₁₋₂ [k€] | C ₂₋₁ [k€] | C ₂₋₂ [k€] | C ₂₋₃ [k€] | C ₂₋₄ [k€] | C ₂₋₅ [k€] | C ₂₋₆ [k€] |
| BEV with columns | 15 | 497 | 1800 | 600 | 1800 | 1890 | 120 | 0 | 450 | 189 |
| BEV with columns + pantograph | 15 | 497 | 1800 | 845 | 1800 | 1890 | 120 | 0 | 575 | 189 |
| HEV | 12 | 617 | 7600 | 0 | 1584 | 3322 | 96 | 0 | 0 | 0 |
| HEV Mild | 12 | 617 | 5600 | 0 | 1296 | 3322 | 96 | 0 | 0 | 0 |
| Diesel | 12 | 921 | 4400 | 0 | 1728 | 3171 | 0 | 0 | 0 | 0 |
| CNG-slow charge | 12 | 783 ^b | 2000 | 370 | 1800 | 880 | 0 | 60 ^c | 36 | 152 |
| CNG-fast charge | 12 | 783 ^b | 2000 | 530 | 1800 | 880 | 0 | 60 ^c | 36 | 152 |
| CNG with L-CNG system on loan | 12 | 783 ^b | 2000 | 0 | 1800 | 1606 | 0 | 60 ^c | 0 | 13.3 |
| FCEV with charging infrastructure | 8 | 210 | 10,625 | 103,500 | 4272 | 4339 | 0 | 0 | 49.6 | 21.9 |
| FCEV with charging infrastructure + production plant | 8 | 210 | 10,625 | 107,200 | 4272 | 0 | 0 | 0 | 529.6 | 24.3 |
| Type of impact^d | B | B | C | C | C | C | C | C | C | C |

^a For level 2 criteria, the weight is the product of level 1 wt for the corresponding Level 2. For instance, for Bus investment the corresponding weight is computed as 0.45 (the weight corresponding to the level 1 cost criterion) x 0.14 (the weight of the level 2 Bus investment criterion).

^b The impact of CNG in terms of gCO₂/km has been estimated as 15% less than the value for Diesel (“Webinar, alternative fuels in the post-Covid-19 scenario; the point on natural gas”).

^c Whole fleet considered.

^d C=Cost, B=Benefit.

Table 11
Decision Matrix for interurban services.

| Weights of Criterion* | 0.37 | 0.21 | 0.067 | 0.047 | 0.066 | 0.054 | 0.086 | 0.043 | 0.030 | 0.027 |
|-------------------------------------|-----------|--------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Fuel alternatives | A [years] | B [gCO ₂ /km] | C ₁₋₁ [k€] | C ₁₋₂ [k€] | C ₂₋₁ [k€] | C ₂₋₂ [k€] | C ₂₋₃ [k€] | C ₂₋₄ [k€] | C ₂₋₅ [k€] | C ₂₋₆ [k€] |
| HEV | 12 | 450 | 6900 | 0 | 1632 | 3876 | 96 | 0 | 0 | 0 |
| HEV Mild | 12 | 450 | 5100 | 0 | 1344 | 1876 | 96 | 0 | 0 | 0 |
| Diesel | 12 | 671 | 2000 | 0 | 1824 | 3721 | 0 | 0 | 0 | 0 |
| CNG-fast charge | 12 | 570** | 920 | 530 | 1920 | 990 | 0 | 60*** | 36 | 171 |
| CNG with L-CNG system on loan | 12 | 570** | 920 | 0 | 1920 | 1806 | 0 | 60*** | 0 | 15 |
| LNG | 12 | 570** | 1040 | 1000 | 1920 | 1806 | 0 | 0 | 36 | 15 |
| LNG with production plant (on loan) | 12 | 570** | 1040 | 0 | 1920 | 1786 | 0 | 0 | 0 | 0 |
| Type of impact | B | B | C | C | C | C | C | C | C | C |

*, ** and *** As in Table 10.

Table 12
Global concordance and discordance index for urban buses.

| Fuel alternatives | With funding | | Without funding | |
|-------------------------------|------------------|------------------|------------------|------------------|
| | \widehat{Ic}_i | \widehat{Id}_i | \widehat{Ic}_i | \widehat{Id}_i |
| BEV with columns | 2.846 | -0.902 | 1.273 | -0.672 |
| BEV with columns + pantograph | 2.625 | -0.466 | 2.598 | -0.236 |
| HEV | 0.249 | -1.991 | 3.002 | -1.576 |
| HEV Mild | 0.521 | -0.910 | 2.843 | -1.928 |

Table 13
Global concordance and discordance index for interurban buses.

| Fuel alternatives | With funding | | Without funding | |
|-------------------------------------|------------------|------------------|------------------|------------------|
| | \widehat{Ic}_i | \widehat{Id}_i | \widehat{Ic}_i | \widehat{Id}_i |
| HEV Mild | 0.853 | -0.500 | 0.788 | -0.500 |
| LNG with production plant (on loan) | 0.230 | -3.556 | 0.230 | -3.556 |

5. Discussion

Based on Level 1 and Level 2 cost criteria, lifecycle, and emissions, the best fuel alternatives for urban and interurban bus services were found.

In the case of the ‘with funding’ ranking, BEVs emerged as the most viable alternative for urban bus services, especially when electric charging stations are available. This conclusion is supported by both the global concordance/discordance index method and the WSM. The results show how this technology can be widely used because it is the most

competitive in terms of vehicle lifecycle, environmental advantages, and fuel costs. Criteria weighting showed high purchase costs, which, however, did not affect the benefits offered by the previous parameters. Moreover, the fact that government incentives and technological evolution would enable increasing the competitiveness and autonomy of this fuel alternative, even in interurban areas, is clear. Generally, urban bus fleet ranking showed how BEVs (with columns + pantograph or only with columns) were the most preferred options followed by HEVs. The most feasible option identified for interurban bus services was mild Hybrid Electric Vehicles (HEV), as determined by both the concordance/discordance index method and the WSM. Furthermore, results showed how HEV Mild fuel alternatives were competitive both in urban and interurban service. Even though the rankings were similar as suggested by Lanjewar et al. (2015) and Tzeng et al. (2005) using TOPSIS, they were specific to the Italian case and the PTCs’ perspective. Comparing these results with the Italian registration trends, it is evident how this technology is gaining ground in this market, although it has not yet surpassed the others. Actually, it is second only to D, for both urban and interurban service, even from the results of the questionnaires. This is made even more clear if we consider that the hybrid vehicles combine the advantages of diesel, with which it is possible to travel long distances without infrastructure, with the advantages of BEVs, which mainly include energy recovery during braking along with reduced environmental impact, making it a valid transitional technology. Results in interurban bus services confirmed several studies (Lajunen, 2014; McKenzie and Durango-Cohen, 2012; Lajunen and Lipman, 2016). In these papers, diesel hybrid buses (mild) were shown to be the best immediate choice concerning D where dependence on fossil fuels,

Table 14
WSM results for urban services.

| Fuel alternatives | Specific | With funding | | Without funding | |
|-------------------|---|--------------|---------|-----------------|----------------|
| | | WSM | Ranking | WSM | Ranking |
| BEV | with columns | 0.688 | 1 | 0.665 | 1 |
| | with columns + pantograph | 0.682 | 2 | 0.658 | 2 |
| HEV | Mild | 0.547 | 3 | 0.568 | 3 |
| | – | 0.526 | 4 | 0.551 | 4 |
| CNG | with L-CNG on loan for use | 0.460 | 5 | 0.458 | 6 ^a |
| Diesel | – | 0.449 | 6 | 0.468 | 5 ^a |
| CNG | slow charge | 0.439 | 7 | 0.438 | 7 |
| | fast charge | 0.439 | 8 | 0.437 | 8 |
| FCEV | with charging infrastructure | 0.331 | 9 | 0.331 | 9 |
| | with charging infrastructure + production plant | 0.309 | 10 | 0.309 | 10 |

^a In the case of ‘Without funding’ these alternatives changed the position in the ranking as opposed to ‘With funding’.

Table 15
WSM results for interurban services.

| Fuel alternatives | Specific | With funding | | Without funding | |
|-------------------|---------------------------------|--------------|---------|-----------------|----------------|
| | | WSM | Ranking | WSM | Ranking |
| HEV | Mild | 0.814 | 1 | 0.835 | 1 |
| LNG | with production plant (on loan) | 0.799 | 2 | 0.772 | 2 |
| HEV | – | 0.761 | 3 | 0.761 | 3 |
| CNG | with L-CNG on loan for use | 0.756 | 4 | 0.742 | 4 |
| LNG | – | 0.721 | 5 | 0.695 | 5 |
| CNG | fast charge | 0.691 | 6 | 0.678 | 7 ^a |
| Diesel | – | 0.667 | 7 | 0.679 | 6 ^a |

^a In the ‘Without funding’ scenario, these alternatives changed their positions in the ranking compared to the ‘With funding’ scenario.

environmental emissions, maintenance, and energy costs represent a weakening of their future competitiveness. Nevertheless, they are well-suited for short-term policy objectives and serve as a stepping stone toward a fully electrified system. Consequently, these findings also have implications for programming in climate policy management. Overall, although the criteria weights showed how the costs of investments in buses and battery changes remain the most critical features, they did not affect the results.

When evaluating the scenario ‘without funding,’ the analysis excluded national and/or European funding for each fuel option. According to the global concordance and discordance indices, the preferred alternative in the urban bus scenario was HEV, followed by BEV (Table 12), mirroring the findings in the “with funding” case. These results might depend on the reduced environmental impact that, thus, mitigates the higher cost of vehicle purchase with respect to other technologies. In interurban bus services, the global concordance and discordance indices confirmed previous results (Table 13). Hence, HEV Mild and LNG with production plant (on loan) technologies were preferred. Additionally, the results describe the relevance of environmental impact, which fully supports these fuel options. Besides, the ‘with funding’ scenario assumed the absence of funding for hybrid vehicles, which was considered instead only for other technologies. As a result, the range that led support to the greater competitiveness (in overall terms, including pollutant emissions) of hybrid HEVs was further strengthened. When the outcomes were provided by the WSM (Tables 14 and 15), in the urban scenario, they confirmed previous results that all alternative fuel options other than diesel were favourable. However, diesel still held a higher position than CNG because the latter is characterized by high infrastructure costs. Similarly, the results in the interurban scenario confirmed the previous ranking.

Here a specific comment concerning hydrogen technology is called for. Although it appeared to be the most disadvantaged technology for urban service (as also indicated by Büyüközkan et al., 2018), if it was supported by economies of scale that would enable the reduction of purchase and operating costs, it would be comparable with other types of fuel alternatives (Ally and Pryor, 2007). The fuel cost of hydrogen in

the Italian scenario represents a substantial difference compared to some other European realities such as Germany, which having produced the fuel gas as an industrial waste product, was able to halve its cost. The effort made by German manufacturers is clearly evident considering the national goal for 2030 to make hydrogen an alternative energy source. To do this, Germany fixed a level of electrolysis at 5000 MW which, by 2040, should be raised to 10,000 MW, with the aim, therefore, to become the number one global supplier of hydrogen, as was proposed by the German government in 2020. The European Commission aims to support the transition to hydrogen mobility, in the following ways. First, with the development of hydrogen refuelling stations and fuel-cell vehicles. Then with the cover and the possibility, through the European Hydrogen Bank, to lower the cost differential between renewable hydrogen and fossil fuels for early projects. This would be accomplished via an auction system for renewable hydrogen production, offering support to producers through a fixed-price payment per kilogram of hydrogen produced over a maximum period of 10 years of operation. The pilot actions, which are currently being designed, and which are backed by €800M from the Innovation Fund, are due to be launched in autumn 2023. The Bank will develop an EU auction platform that provide “auctions-as-a-service” for Member States. This will be accomplished by utilising resources from both Innovation Fund and Member State, to finance renewable hydrogen projects, all while adhering to EU state aid rules.

The differences in the results on best alternative fuel choices can be explained by the different criteria considered and the experts involved. For instance, Büyüközkan et al. (2018) highlighted the relevance of energy availability and air and noise pollution concluding that CNG is the best fuel alternative for urban services in the 2-additive Choquet Integral model and then LPG using TOPSIS. These results could be interpreted as being compatible with the perspectives of the experts involved. Indeed, Ozdagoglu et al. (2022) reported that there were significant differences among the decision-making experts, i.e., bus owners and bus drivers, because they considered different issues as critical. For instance, though the bus drivers were not involved in the economic issues concerning fleet investment their opinions on services

and trip quality were considered. Nevertheless, the results of application in Italy revealed that the perceptions of PTCs were primarily focused on financial criteria and, then on the lifecycle of the buses. Other studies verified similar relevance of the criteria found in this study. For instance, though [Aydin and Kahraman \(2014\)](#) obtained the Initial cost and Maintenance cost as weighted criteria, the authors observed different best alternatives in CNG. Differences in ranking can also be explained by local features: the closer to main producers of certain types of fuel or advanced industry, e.g., in the previous example of FCEVs, the more acceptable that alternative became. This implies different path to achieve climate goals, to adjust by local differences ([Tian et al., 2023](#)).

Despite that, these findings clearly imply that there are still some policy and practice issues. Usually, PTCs are not inclined to switch bus fleets without incentives, yet the results showed BEV and HEV fuel alternatives to be economically advantageous in urban services even without funding. Therefore, PTCs should fully consider the economic and sustainability implications of alternative fuels during the decision-making process. The question can be synthesised as a contrast regulations-costs- knowledge of PTCs', i.e., their poor awareness on innovative and alternative fuels ([Edwards and Mackett, 1996](#); [Corazza et al., 2016](#)). The longer-term perspective of decreasing technological costs should also be taken into account. Indeed, the application of subsidies might make the switch to alternative fuels even more affordable. Therefore, evaluation models should be implemented as common practice. Nevertheless, we cannot exclude the importance of integrated urban and regional plans and policies on infrastructure investments or on the application of advantageous tax mechanisms capable of triggering or accelerating the implementation of sustainable decarbonisation systems ([Xylia and Silveira, 2017](#)). Specifically, fundings regularity might make the switch to alternative fuels even more affordable in several company size scenarios, for instance, by gradually replacing bus fleet with zero-emission types, manageable in the long run ([Corazza et al., 2016](#); [Elagouz et al., 2023](#)).

6. Conclusions and research perspectives

In pursuit of sustainability in transport systems, and the current competitive market, PTCs face an arduous challenge when designing their fleets of urban and interurban vehicles. Specifically, they need to evaluate which type of traction power supply they should adopt both in terms of the financial advantageousness and the sustainability of the context in which the public transport service operates. Consequently, PTCs should be supported in this decision-making process for the renewal of their fleet based on possible fuel alternatives to be evaluated according to some specific criteria and considering several viewpoints. The literature showed that alternative fuels for the bus fleet could be evaluated according to several approaches. Nonetheless, specific attention to cost details as well as the involvement of a heterogeneous sample of PTCs have not yet been fully elucidated, to our knowledge. To address these issues properly, this study was an attempt to contribute to the literature in a threefold way.

- Evaluation of six alternative fuels for urban and interurban buses (i.e., BEV, FCEV, D, CNG, LNG, and HEV) in the Italian context. These were assessed by a set of criteria regarding environmental impact, vehicle lifecycle, and costs, with the latter being analysed according to purchase, operation, and maintenance items, with and without funding.
- Integration of AHP, ELECTRE I, and WSM in a single method to return the best compromise solution in the choice of alternatives involving highly skilled senior Italian PTC managers in the decision-making process.
- Application of an integrated method for assessment of urban and interurban services to obtain an overall picture of the possible alternatives.

Relevant implications appear to be as follows: (i) the specification of cost criteria measured according to eight specific indicators may help PTC managers to accurately evaluate their options; (ii) the method's high degree of applicability is not strictly linked to the assessment of bus fuel alternatives but can be generalised for other options, in other contexts, according to the preferences of the decision makers involved and when applied to specific routes; (iii) the method enables the structure to be customized (by adding and/or adjusting parameters) according to the specific needs of the analyst and could be easily replicated in different contexts starting from a local environment to a national scenario.

Yet, all in all, this study indicates several interesting developments. First, only the PTC managers are included as experts that make this study a bit focused on the viewpoint of the industry practitioners. However, future research could benefit from including other stakeholders like government administrators and passengers for broader insights into policy formulation, financial support, and service quality. Second, there is the selection of Italian experts: the study is small in scale compared to the large number of PTCs worldwide. Consequently, the study disregarded the possible trade-offs between the specificity of the local and general conditions or the comparability of the selected parameters. Nevertheless, Italy was selected as the context for this study because it offers a favourable environment for analysing alternative fuel choices for fleet renewal. The country's regulatory framework supports sustainable transportation, pressuring PTCs to explore alternative fuels. The varied regulations, geography and demographics in Italy present both opportunities and challenges for alternative fuel adoption in public transportation that PTCs might adopt. Additionally, the evolving infrastructure (e.g., investing in electric vehicle charging stations) and policy landscape in Italy provide valuable insights for alternative fuel viability and implementation. However, caution is needed when extrapolating results to other markets, due to contextual factors like stakeholder dynamics, infrastructure accessibility, regulatory environments, and economic conditions.

Third, the choice of vehicles could differentiate the results. For instance, [Hamurcu and Eren \(2020\)](#) and [Gong et al. \(2020\)](#) noticed that the same fuel alternative can differ among different kinds of vehicles that might have different performance. Moreover, in this study, major attention was devoted to cost parameters as opposed to other studies where major attention was paid to environmental impact and lifecycle parameters (e.g., [Tong et al., 2017](#); [Nordelöf et al., 2019](#)). Finally, the evaluation of new fuel alternatives such as hydro methane, and bio-methane was suggested.

CRedit authorship contribution statement

Fabio Borghetti: Writing – review & editing, Validation, Supervision, Project administration, Data curation. **Martina Carra:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Carlotta Besson:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Elisabetta Matarrese:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Roberto Maja:** Visualization, Supervision, Project administration. **Benedetto Barabino:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization, Project administration.

Declaration of competing interest

Declare no conflict of interest, financial or otherwise.

Data availability

The authors do not have permission to share data.

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