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A techno-economic life cycle assessment of H2 fuelled and electrified urban buses

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HIGHLIGHTS

- TCO and LCA analyses of urban bus powertrains with realistic energy consumption.
- Potential of hydrogen and electrification in decarbonizing urban transport.
- Impact of future market trends and different energy mixes on LCA.
- Hydrogen vehicles may be optimal if hydrogen costs drop to €4/kg.
- BEVs remain the most cost-effective option if hydrogen stays niche.

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ABSTRACT

Nowadays, several technologies based on powertrain electrification and the exploitation of hydrogen represent valuable options for decarbonizing the on-road public transport sector. The considered alternatives should exhibit an effective benchmark between CO_2 reduction potential and production/operational costs. Conducting a comprehensive Total Cost of Ownership (TCO) analysis, coupled with a thorough Life Cycle Assessment (LCA) is therefore crucial in shaping the future for cleaner urban mobility. From this perspective, this study compares different powertrain configurations for a 12 m urban bus: a conventional diesel Internal Combustion Engine Vehicle (ICEV), a series hybrid diesel, two hydrogen-based series hybrid vehicles: a Hydrogen Hybrid Electric Vehicle featuring an H2-ICE (H2-HEV) or a Fuel Cell Electric Vehicle (FCEV), and a Battery Electric Vehicle (BEV). Moreover, a sensitivity analysis has been conducted on the carbon footprint for power generation, considering also the marginal electricity mix. In addition, prospective LCA and TCO elements are introduced by addressing future technological projections for the 2030 horizon. The research reveals that, as of today, the BEV and hydrogen-fueled vehicles have comparable environmental impacts when the marginal electricity mix is considered. The techno-economic analysis indicates that, under current conditions, FCEVs and H2-HEVs are not cost-effective for CO_2 reduction unless powered by renewable energy sources. However, considering future technological advancements and market evolution, FCEVs offer the most promising balance between economic and environmental benefits, particularly if hydrogen prices reach €4 per kilogram. If hydrogen-powered vehicles remain a niche market, BEVs will be the most viable option for decarbonizing the transport sector in most European countries.

Abbreviations: AEM, Average Electricity Mix; APU, Auxiliary Power Unit; BEV, Battery Electric Vehicle; BoP, Balance of Plant; CAPEX, CAPital Expenditure; CF, Carbon Footprint; CI, Carbon Intensity; CNG, Compressed Natural Gas; FC, Fuel Cell; FCEV, Fuel Cell Electric Vehicle; FU, Functional Unit; GHG, Green House Gas; H2-HEV, Hydrogen Hybrid Electric Vehicle; HDV, Heavy Duty Vehicle; HEV, Hybrid Electric Vehicle; HVO, Hydrogenated Vegetable Oil; ICE, Internal Combustion Engine; ICEV, Internal Combustion Engine Vehicle; IEA, International Energy Agency; LCA, Life Cycle Assessment; LDV, Light Duty Vehicle; LFP, Lithium iron phosphate; LTO, Lithium Titanium Oxide; MEM, Marginal Electricity Mix; NMC, Nickel Manganese Cobalt; OPEX, Operational EXpenditure; PEM, Proton Exchange Membrane; PGM, Platinum Group Metals; PM, Permanent Magnet; SCR, Selective Catalytic Reduction; SMR, Steam Methane Reforming; SoC, State of Charge; TCO, Total Cost of Ownership; TTW, Tank-To-Wheel; WRI, World Research Institute; WTT, Well-To-Tank; WTWs, Well-To-Wheels.

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1. Introduction

Decarbonizing the transport sector is currently one of the fundamental steps in pursuing the mitigation of climate change. According to the International Energy Agency (IEA), transportation accounts for approximately 24 % of global energy-related carbon dioxide emissions, with road transport being the largest contributor with a share of 74 % [1]. In this context, lorries, buses, and coaches play a significant role, responsible for over 6 % of total European Greenhouse Gas (GHG) emissions, equivalent to a quarter of the whole GHG emissions from the European Union (EU) transport sector [2]. Nevertheless, a study conducted by the World Resources Institute (WRI) revealed that urban transport emissions are projected to rise by nearly 60 % by 2050 if significant measures are not implemented [3]. To address this issue, the EU has introduced stronger CO_2 emission standards for Heavy-Duty Vehicles (HDVs), encompassing smaller trucks and urban or suburban buses. The proposal aims for a 90 % reduction in CO_2 emissions per kilometer from new HDVs by 2040, compared to a baseline spanning from mid-2019 to mid-2020, with intermediate targets set for 2030 (45 % reduction) and 2035 (65 % reduction) [4]. Within this framework, the synergetic exploitation of decarbonized energy carriers (e.g., hydrogen) and powertrain electrification has the potential for transitioning public transportation fleets towards more sustainable mobility, aligning with current legislative targets. Battery Electric Vehicles (BEVs) offer promise in decarbonizing the Light-Duty Vehicle (LDV) sector, while their viability remains limited in applications where payload and operational range are primary concerns [5]. At the same time it has to be noted that according to BloombergNEF, electric buses are expected to account for 67 % of all municipal bus sales globally by 2040 [6]. This surge in adoption should be driven and supported by advancements in battery technology, to obtain higher energy density batteries, abatement of capital costs, and an increasing share of renewable energies for electricity production [7]. By contrast, and despite its low energy density, hydrogen emerges as a compelling alternative fuel for the HDV sector, ensuring zero carbon-based emissions with production pathways leveraging renewable energy sources [8]. In the urban public transportation sector, Fuel Cell Electric Vehicles (FCEVs) exhibit significant advantages over BEVs, including weight reduction, extended range, and quicker refueling [9]. Moreover, exploiting hydrogen to power Internal Combustion Engines (ICEs) presents additional benefits such as fuel contamination tolerance, and compatibility with existing powertrain production lines, thanks to familiar technologies and parts from current Internal Combustion Engine Vehicles (ICEVs) [10,11]. However, a primary concern regarding hydrogen vehicles revolves around the necessity for new infrastructure to facilitate hydrogen distribution and refueling. Nevertheless, in the case of urban buses, the issue of tank refueling is mitigated, particularly since captive fleets can centralize the fuel stations [12].

In this context, the integration of Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) is essential to select appropriate powertrain alternatives for the so-called “clean urban buses” [13]. LCA provides a comprehensive evaluation of the environmental impacts of each powertrain option throughout its entire life cycle, tracing emissions from production to disposal. Similarly, the TCO analysis takes into account all costs associated with each powertrain alternative over its lifespan, including initial purchase price, operational expenses, and maintenance costs. Integrating both LCA and TCO allows for a comprehensive assessment that considers environmental impacts alongside economic factors, therefore preventing the impact displacement of one phase of the vehicle’s life to another. For the road sector, the current legislation assesses CO_2 and pollutant emissions solely based on what comes out of the vehicle’s tailpipe, following a Tank-to-Wheel (TTW) approach. As a result, electricity-driven vehicles are often classified as “Zero-Emission Vehicles” (ZEVs), despite the fact that this method overlooks emissions from energy production and supply. To ensure a scientifically sound and unbiased evaluation of electrification in transport, a technology-neutral Well-to-Wheels (WTWs) approach is essential:one that accounts for emissions and savings across the entire energy lifecycle, from fuel production to final use. [14]. As an example, in the case of a vehicle powered by fossil fuels, the majority of its environmental impact typically comes from the use phase, while the production and End-of-Life (EoL) treatment phases contribute to a lesser extent: for instance, a study conducted by Nordelof et al. [15] concerning the climate change impact of buses revealed that the use phase accounted for 90 % of the impact for a conventional diesel bus. Conversely, for BEVs (operating in Sweden), the use phase would only contribute to 30 % of the total GHG impact, due to the lower emissions associated with the electricity production and consequent use.

Moreover, although BEVs and FCEVs have no tailpipe emissions, and H2-HEVs produce no tailpipe CO_2 through combustion, the emissions associated with the production of the energy vector (i.e., hydrogen and electricity) can lead to significant environmental impact [16]. Restricting such comparison to the TTW analysis only could potentially result in misleading conclusions. Indeed, the fuel production process, which accounts for a great share of electricity (e.g., e-fuel, hydrogen by electrolysis) could exhibit higher energy consumption and CO_2 emissions in the Well-To-Tank (WTT) phase when compared to diesel fuel [17]. This is because the environmental impact of fuel production pathways during the WTT stage may be significantly impacted by the fuel production stage [18]. As an example, Pederzoli et al. [19] demonstrated that hydrogen-powered buses have the potential to reduce CO_2 emissions, compared to diesel buses, only if renewable resources are used to produce the fuel. Regarding BEVs, the value of the electricity grid Carbon Intensity (CI), which represents the CO_2 emissions per unit of electricity produced (gCO_2/kWh), highly affects the results of an LCA analysis [20,21]. As a matter of fact, the benefits of electrification may be negligible or even negative if the electricity system has a high CI [21]. In addition, the majority of the LCA studies are based on average GHG emission values for specific regions, reflecting the overall electricity mix, while neglecting the effects of additional demand and charging times on the electricity grid. It has been demonstrated that considering the additional electricity demand for high-capacity battery recharging could overturn the results of the LCA comparison, disadvantaging BEVs with respect to conventional powertrains [22]. To estimate the accurate CO_2 emissions stemming from charging a BEV, the instantaneous CO_2 emission rate must be considered, together with the impact of the Marginal Electricity Mix (MEM), i.e. the CO_2 emissions associated with the production of the additional demand from the electricity. A comparative study on the LCA emissions of BEVs, ICEs, and FCEVs for a passenger car application demonstrated that marginal GHG emissions can be twice as much as the average emissions [23]. Furthermore, according again to [23], for a scenario involving one million cars, marginal emissions for BEVs could be three times higher than the average emissions.

As previously stated, a comprehensive TCO analysis should be conducted in conjunction with the LCA to establish a benchmark comparing environmental and cost impacts. Considering the costs of introducing a new technology is also essential for it to be deemed acceptable from the policymaking perspective. In applications such as urban buses, where a long vehicle lifespan is expected, the use phase is expected to have a predominant impact, particularly for diesel and hydrogen-based powertrain options. Additionally, the evolution of future hydrogen prices typically exhibits considerable variability, for instance, under the assumption of the presence or absence of incentives and supporting actions in the legislation framework. Moreover, the evolution of the costs of hydrogen-related technologies is heavily dependent on the assumed market penetration [24]. Similarly, there is significant variability in the environmental and economic impact of large-capacity batteries used in BEVs, as well as in their cost projections. According to a BloombergNEF survey [25], the average price of lithium-ion batteries varies by application: the specific battery cost for a passenger car could cost twice as much as one for an urban bus. Additionally, the survey indicates that bus battery prices may increase by 50 % if they are manufactured outside of China [25]. Considering all these aspects, future forecasts about the development and adoption of clean bus alternatives should account for the significant variability in the aforementioned data and prospect different scenarios accordingly.

In this framework, many studies evaluate the LCA impact of fully electric urban buses, or buses powered by renewable fuels, compared to traditional powertrains, while hydrogen buses are not so often included. For instance, a comprehensive LCA of city buses in [15] compares the environmental impact of BEVs and ICEVs, fueled by conventional diesel or Hydrotreated Vegetable Oil (HVO), identifying a breakeven point for the Global Warming Potential (GWP) between powertrain alternatives based on grid CI. A more detailed analysis of fully electric buses has been presented in [26], evaluating the impact of varying battery chemistry, size, and vehicle lifetime, as well as the number of battery replacements on the overall vehicle LCA. The same study concludes by coupling optimal battery chemistries with different sizes and ranges. Furthermore, Gustaffson et al. [27] analyzed the WTWs climate performance of gas and electric vehicles in Europe, considering the use of biomethane and its production systems alongside traditional diesel and Compressed Natural Gas (CNG) vehicles. Their results indicate that BEVs are more favorable in countries where high shares of renewable energy are present in the grid mix, presenting the GWP of the vehicles as a function of the electricity system's CI. Similar conclusions are drawn by the same authors in [20]; in the herein study hydrogen has been considered as a fuel for FCEVs, emphasizing the crucial role of the surrounding energy system in transitioning towards decarbonized transport. Additionally, Pederzoli et al. [19] analyzed Fuel Cell (FC) city buses with various hydrogen production options, highlighting the significance of "green" hydrogen as a future urban mobility solution.

Regarding the cost aspect, an example of the complexity of technology selection for fully electric buses has been illustrated in [28] which shows a wide range of variability in battery costs and their future market projections. In this context, Kim et al. [29] predict a 25 % decrease in the TCO for electric buses by 2030 compared to conventional diesel vehicles. They also suggested that TCO parity between FC and diesel buses can be achieved only with large-scale infrastructure and significantly reduced hydrogen costs. A variability in hydrogen price has also been considered in [30] based on the hydrogen production pathway for an FC bus application, highlighting the significant impact on the WTT phase and its influence on the comparative analysis with BEVs and ICEVs. Due to the high reliance of the obtained results on the stated hypotheses, various case studies are situated within a defined scenario. For instance, Borghetti et al. [31] considered a case study in Brescia, Italy, evaluating the best alternative to replace a conventional diesel bus fleet with either BEVs or FCEVs, while also projecting forecasts for 2030. Additionally, a scenario analysis of German public transportation suggested that starting in 2035, FC buses will become more economically attractive than diesel buses [32]. Finally, Coppola et al. [33] presented a comprehensive methodology to identify suitable pathways for renewing existing bus fleets with BEVs and/or FCEVs. A multicriteria analysis has been developed, incorporating real local geographical context and bus fleet characteristics as inputs for both life-cycle economic and environmental analyses. The results demonstrated that fleet renewal policy choices towards new clean-fuel vehicles are complex due to the significant variability in input data, and obtaining meaningful results requires careful consideration of the location, time frame, and specific application chosen for the analyzed scenario.

In this context, the present study offers a novel perspective on the economic and environmental assessment of powertrain alternatives for urban transport, with a specific focus on city buses. This research evaluates the cost-effectiveness of reducing CO_2 emissions across the entire life cycle of different powertrain configurations, including BEVs, FCEVs, and hydrogen-based ICEVs, compared to conventional diesel options. The primary objective is to provide insights that can inform and support emerging transport policies, which are shifting towards a full life-cycle emissions approach and assessing the economic feasibility of sustainable alternatives for HDVs [34]. The key contributions of this study, which distinguish it from existing research, can be summarized as follows:

- Integrated environmental and economic evaluation: a comprehensive benchmarking approach is introduced that integrates both environmental and economic assessments for sustainable urban transport solutions. It evaluates the potential of electricity and hydrogen in decarbonizing public transport, considering not only Proton Exchange Membrane (PEM) fuel cells but also hydrogen combustion in ICEs and different hydrogen production pathways;
- Geographically contextualized analysis: real-world geographical factors are considered by assessing the impact of different European electricity mixes on LCA results and energy vectors prices. A detailed case study examines both average and marginal electricity mixes in Italy;
- Real-world driving conditions: real driving conditions and service characteristics of urban buses are included, analyzing their performance across three distinct driving cycles representative of urban transportation;
- Future-oriented insights: outcomes are projected up to 2030, incorporating multiple scenarios that reflect anticipated market trends, advancements in hydrogen technology, reductions in battery costs and environmental impact, and fuel price fluctuations. These projections provide crucial forward-looking insights to guide strategic planning and policymaking.

The article is structured as follows: Section 2 proposes a description of the "Materials and Methods," outlining the framework of the LCA and TCO analysis in terms of goal and scope, case study, system boundaries, and data acquisition process. Section 3 presents the results, beginning with the production phase and proceeding to a detailed WTT analysis of the considered hydrogen production pathways. The comprehensive LCA and TCO results are then discussed across three different driving cycles, incorporating the uncertainties related to the sensitivity analysis and future forecasts. Finally, Section 4 summarizes the conclusions.

2. Materials and methods

2.1. Goal and scope

In order to achieve the primary objective of this study, a reliable methodology has been defined to investigate and compare different powertrains and technology options for the decarbonization of the public transport sector. This involves finding a compromise between their environmental footprint in terms of GHG emissions, alongside production and operating costs. In particular, three powertrain options have been considered as "clean solutions" to power a 12 m urban bus:

(i) a series hybrid bus equipped with a fuel cell (*FCEV)*,
(ii) a series hybrid bus equipped with a hydrogen ICE (*H2-HEV*), and
(iii) a battery electric vehicle (*BEV*).

These options are compared against a conventional diesel (*ICEV)* and a diesel Hybrid Electric Vehicle (*HEV*), in terms of LCA and TCO performance. Furthermore, the research project aims to assess various hydrogen production pathways and the impacts of variations in the CI of the electricity grid. Specifically, all LCA results are presented as a function of grid CI, ranging from 0 to 650 gCO_2/kWh. This range represents, on one end, a fully renewable energy mix and, on the other, the current Average Energy Mix (AEM) of Poland or India, among the current highest CIs values in Europe and in the world [35]. This approach allows for presenting the results under a full WTWs approach. Two hydrogen production processes have been considered:

(i) Steam Methane Reforming (SMR) and
(ii) Electrolysis.

Additionally, the AEM for the main European countries was compared with the MEM for both hydrogen production and BEV charging, together with a 100 % renewables energy mix as a limit comparison for "green" hydrogen/electricity small-scale production [36]. In addition, perspective LCA and TCO elements are added by providing different timeline scenarios, including a sensitivity analysis on parameters such as Carbon Footprint (CF) and costs, the penetration of hydrogen-related technologies, and variations in fuel and battery prices.

2.2. Case study: reference vehicle and powertrain characteristics

In the present work, a 12 m urban bus has been chosen with its main specifications listed in Table 1.

In the whole analysis, different powertrains have been considered, starting from standard diesel configurations employed as the most widespread option in the current bus market [13] and proposing "clean" alternatives, in line with a similar study by the Authors in [37]. Fig. 1 presents a schematic layout of the powertrains.

At first, a conventional large displacement ICEV (Fig. 1a) has been selected as a benchmark. To highlight the benefits of hybridization for bus architecture, a HEV with a series architecture (Fig. 1c) has also been analyzed, featuring a downsized diesel ICE as an Auxiliary Power Unit (APU), as defined at first in [38].To evaluate hydrogen's potential as a decarbonizing energy carrier, a third and fourth configurations have been defined, with the same series architecture of the HEV and substituting the APU with a Hydrogen ICE (H2-HEV), or a Fuel-Cell stack (FCEV), respectively. The last powertrain configuration chosen for a so-called "clean bus" is a fully electric vehicle (BEV - Fig. 1b). The choice of this alternative stems from the increasing share of this technology in urban markets. Notably, in 2022, 43.8 % of newly registered buses in Europe were "diesel-free" vehicles, with BEVs constituting 21.8 % of this figure [13]. All the details regarding the specifications of the main components are presented in Appendix A.

In order to evaluate the performance of the proposed solutions, three distinct driving cycles were considered to represent urban bus operations, characterized by a high share of stop phases (ranging between 22 and 27 %) typical of a start-and-stop driving pattern for urban public buses. These mission profiles are depicted in Fig. 2, with detailed driving cycle specifications outlined in Table 2.

The Braunschweig cycle, specifically tailored for urban public transport, is commonly employed in certification programs and research projects [39]. Conversely, the Gillingham Uphill, which is derived from actual GPS data, includes elevation changes and challenging operating conditions marked by higher maximum speeds and energy demands [40]. The MLTB cycle was developed by UK transport authorities to verify the compliance of new vehicles with emissions and fuel economy standards [41]. Differently from the Braunschweig cycle, the MLTB cycle maintains a lower average velocity and covers a shorter distance within a comparable mission duration. A daily range of 200 km is expected on one work shift for each bus, and the storage systems are sized to guarantee no need for recharging or refueling during the daily mission for H2-fuelled powertrains and the BEV (see Appendix A for more details).

Fig. 3 summarizes in a simplified diagram the different vehicle concepts and fueling options considered in the use phase from a WTWs perspective.

Table 1
Vehicle specifications.

Length [m]	12
Curb weight [ton]	12
Fully loaded weight [ton]	18
Passenger capacity [−]	90
Road Load @50 km/h [kW]	16
Lifespan [km]	700,000

2.3. System boundaries

The definition of the system boundaries is shown in Fig. 4 for the LCA and TCO analyses and has been selected to provide a reliable comparison between the different powertrains within a technology-neutral framework. As far as LCA is concerned, a comprehensive cradle-to-grave methodology has been adopted, encompassing all phases of the vehicle lifecycle from production to EoL. For the production phase, the focus was primarily directed on the powertrain components and fuel/energy storage systems, excluding the emissions related to the glider manufacturing.[1] Its impact could be considered not relevant for comparative purposes. In the use phase, a WTWs approach was adopted, including the fuel production process in the analysis. In particular, two pathways for hydrogen production have been simulated (i.e., electrolysis and SMR) and the impact of different energy mixes on electricity production assessed. Finally, the emissions related to vehicle disposal have been considered in the EoL phase.

Additionally, the TCO analysis is divided into two contributions: the CAPital Expenditure (CAPEX) and the OPerating Expenditure (OPEX). CAPEX pertains to the initial investments needed for the different powertrains, while OPEX includes the costs related to fuel sourcing, ordinary maintenance, and powertrain component replacements throughout the vehicle's lifespan. It should be pointed out that the hydrogen-fueled powertrains need new production, supply, and refueling infrastructures. The impact of this aspect on environmental and economic performance has been not directly evaluated in this study but rather included through the actual cost of kg of hydrogen, as a percentage of the final cost, spanning from 5 to 25 % depending on the technology considered. A decrease of this share is expected and accounted for in this analysis in the future, considering the penetration on the market of this energy vector. In addition, the necessity for new dedicated charging infrastructures to facilitate the widespread adoption of electric buses should also be considered; however, the lifetime of refueling and charging infrastructures is expected to determine a limited impact on the initial environmental and economic costs for individual vehicles [29]. Finally, an average bus capacity has been supposed equal for the different powertrains (i.e., 54 passengers, 60 % of maximum capacity), since the full capacity of the different powertrains is comparable and the number of passengers under average travel conditions is assumed to be similar. For this reason, also the revenue from the bus ridership has been excluded from the comparison, as it remains consistent across the considered powertrains. Therefore, the Functional Unit (FU) utilized for evaluating the CF of various powertrains is the quantity of CO_2 emitted per traveled kilometer by each vehicle. This approach simplifies comparisons across different driving profiles and is in line with similar studies [19,26]. The FU employed for TCO analysis is the cost per kilometer traveled by each vehicle, with similar considerations done for the FU of the LCA.

In the context of the temporal dimension of this analysis, it is initially focused on the current situation, considering a limited penetration of emerging technologies (e.g., FC systems, carbon fiber tanks, lithium batteries), with the current average value for the European fuel and electricity prices. Indeed, specific examples of European countries are included in the LCA and TCO analyses to assess the impact of different grid CIs and regional variations in energy carrier prices. Subsequently, a projection for 2030 has been made by forecasting the costs and

[1] The glider is defined as the vehicle chassis built without the powertrain system, and so the ensemble of components common across all architectures. Differences in glider material composition (e.g., lightweight materials for BEVs) have been considered negligible for this application (see life cycle inventory in [15]).

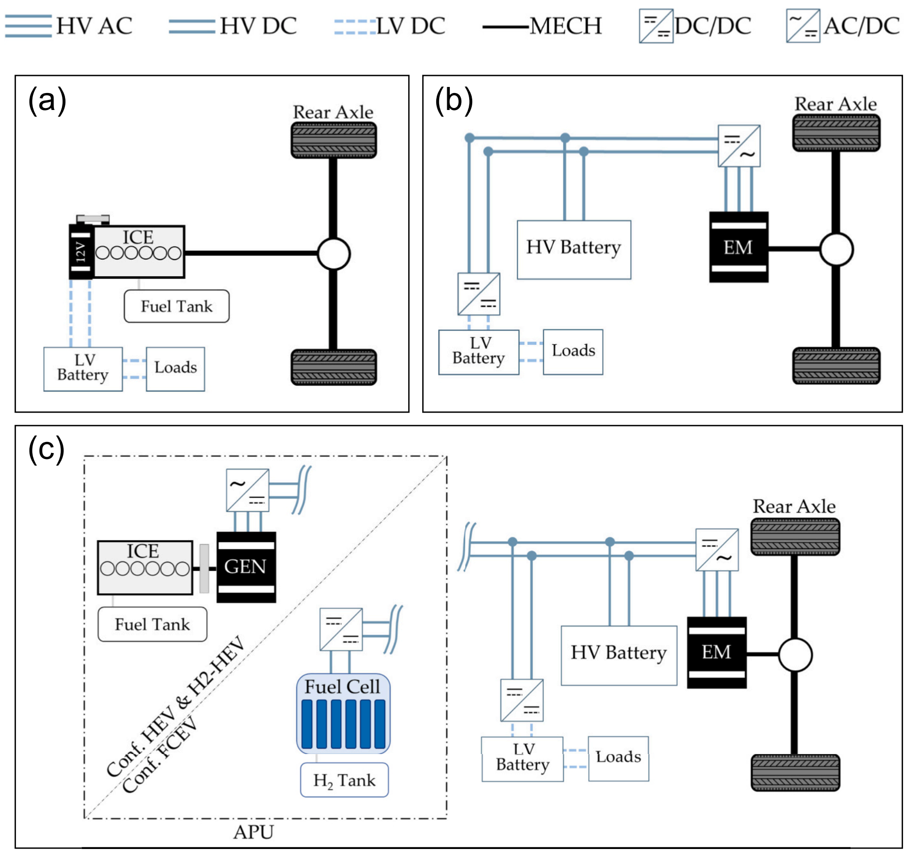

Fig. 1. Layout of the different powertrains. (a) ICE-only powered for the ICEV, (b) full electric for the BEV, (c) hybrid series configurations: the considered APU is a diesel ICE for the HEV, a hydrogen ICE for the H2-HEV, and a FC for the FCEV.

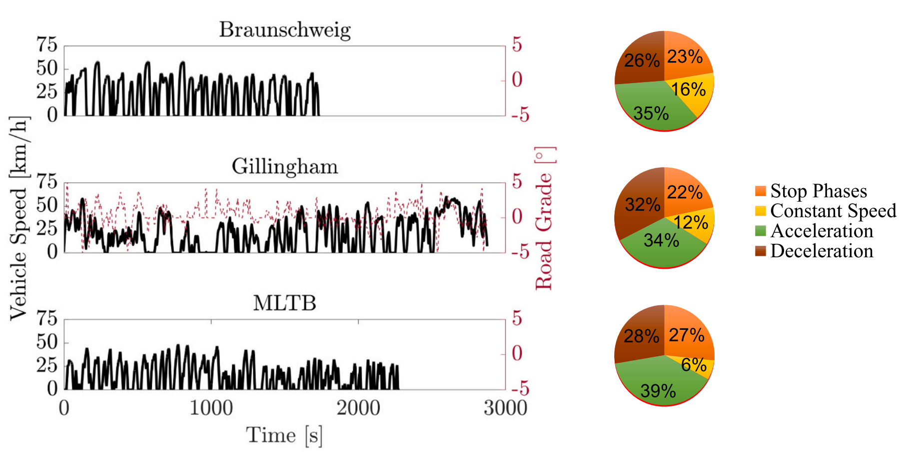

Fig. 2. Vehicle speed and road grade of the considered driving cycles.

environmental impact of emerging technologies, energy vector prices, and grid CIs under “conservative” and “optimistic” scenarios. These projections were based on the expected production volumes by OEMs, following the methodology employed by Miotti et al. [24]. A considerable decrease in hydrogen and electricity prices was assumed in the next years and integrated into the “optimistic” and “conservative” scenarios [42]. Regarding the price of diesel fuel, an ”optimistic” scenario considers a similar value with respect to today, and a “conservative” scenario considers an increase in the diesel price [43,44]. Regarding the CI of the electricity mix, the analysis utilized actual average values found in [45,46] for various countries to evaluate the impact of such differences. Additionally, data for the Italian MEM were included in the comparison [47]. An hourly simulation of energy mix dependence on a typical March day was conducted [48]. This consideration is crucial for hydrogen production and/or BEV recharging, as the timing of grid electricity utilization, especially during off-peak hours, like at night, can significantly impact overall CI. Furthermore, the introduction of BEVs into urban bus fleets may stress existing electricity grids, potentially resulting in increased utilization of marginal generation plants and associated GHG emissions penalties [23]. Looking towards the future scenario (i.e., 2030), a decrease in the CI of advanced economies is expected, following current trends [49]. Two scenarios were identified: an “optimistic” one,

Table 2
Main Features of the considered mission profiles.

	Braunschweig	Gillingham	MLTB
Duration [s]	1740	2875	2281
Distance [km]	10.9	16.6	9.0
Avg. Speed [km/h]	22.5	20.8	14.2
Max Speed [km/h]	58.2	59.9	48.7
Avg. Acc. [m/s^2]	0.2	0.2	0.2
Max Acc. [m/s^2]	2.4	2.3	1.5
Spec. Energy Demand[a] [kWh/km]	0.90	1.05	0.94

[a] Estimated for a 12 m urban bus.

where the grid CIs are halved compared to today [49], and a "conservative" scenario, following a linear decrease as projected by the IEA in the Announced Pledges Scenario (APS) report [50]. The optimistic scenario aligns with the EU's climate targets for 2050, while the conservative scenario represents an intermediate pathway between the current situation and a Net Zero Scenario as defined from the IEA [50]. Specifically, it assumes that all major national commitments announced by countries worldwide will be fully implemented on time. The latter scenario could also take into account a constrained renewable energy supply system, as suggested by [51]. A summary of the temporal scenarios and associated assumptions is provided in Fig. 5, with all the considered values regarding the CAPEX listed in Appendix B.

2.4. Data acquisitions

In this section, life-cycle inventories are provided for each powertrain under comparison.

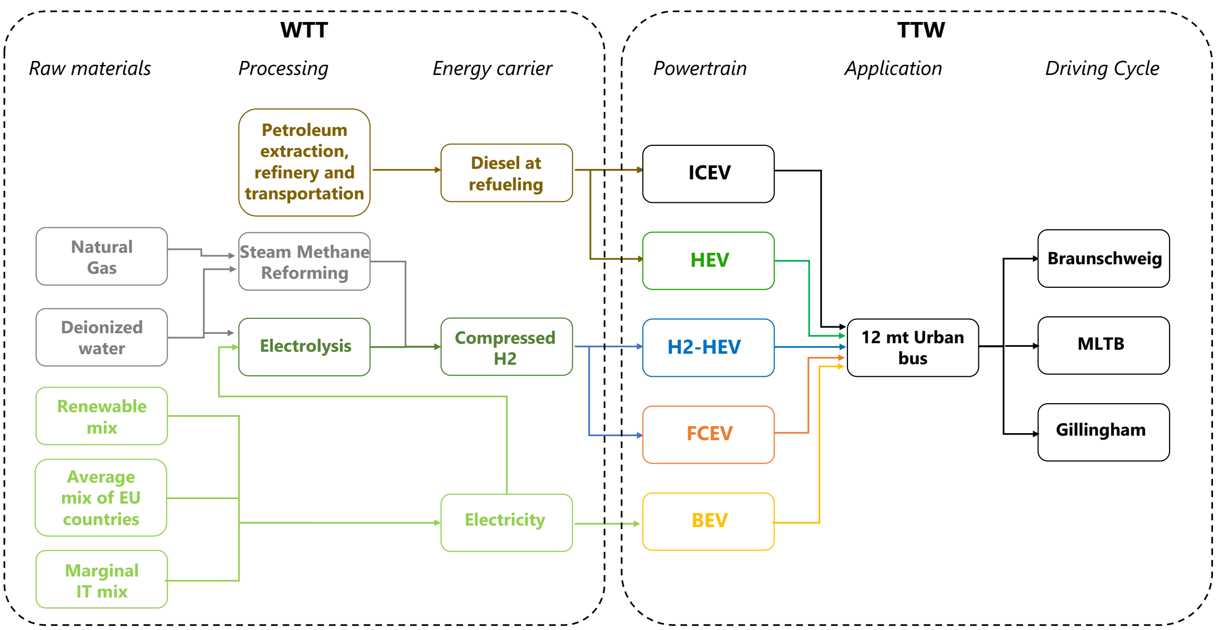

Fig. 3. Focus on the studied scenarios in terms of WTWs analysis for the bus use phase.

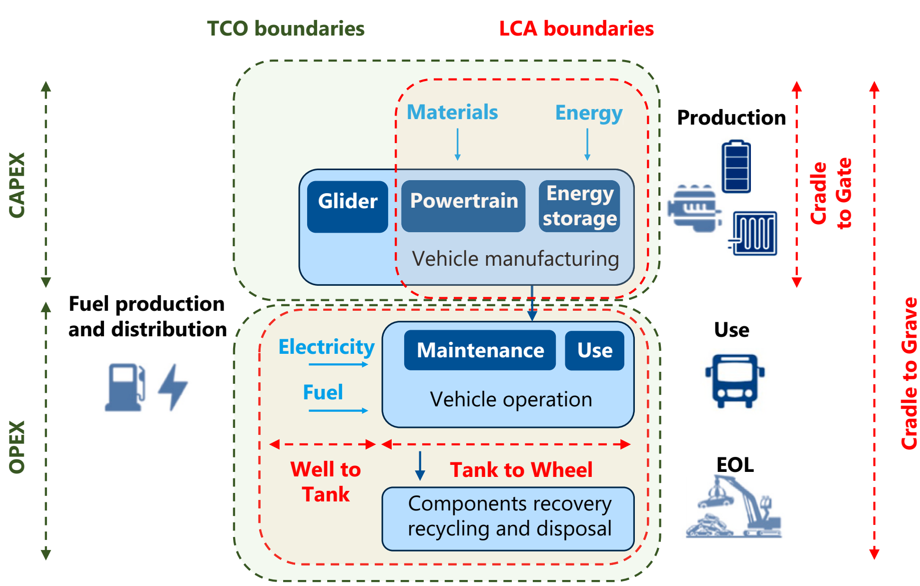

Fig. 4. Considered system's boundaries for the LCA (red lines and boxes) and TCO (green lines and boxes), the glider is only considered in the cost analysis, not influencing the comparison in terms of environmental impact assessment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

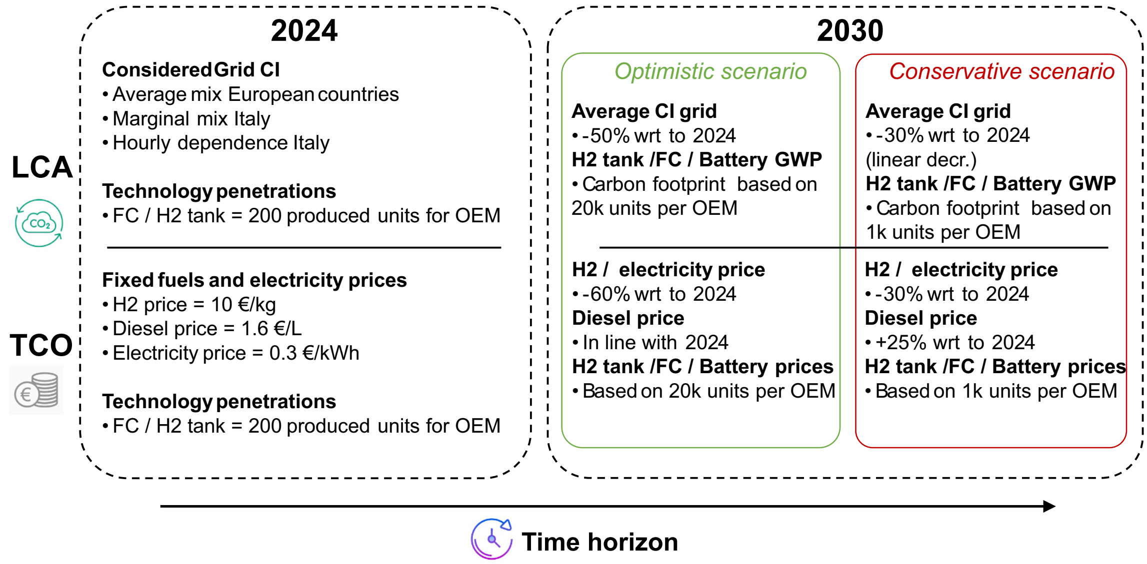

Fig. 5. Summary of the different hypotheses of the LCA and TCO analyses for the current time-horizon scenario, and "conservative" and "optimistic" forecasts for 2030.

2.4.1. Production and EoL phase

Starting from the production phase, no primary data were available regarding the bus components. The environmental and economic costs were therefore derived by properly scaling literature data to fit the current case study. Table 3 provides a summary of the data and sources considered for vehicle manufacturing and all the details are given in Appendix C, together with detailed information about the EoL phase of the main components.

2.4.2. Use and maintenance phase

The use phase can be divided into two stages: WTT (i.e., CF of the fuel production), and TTW (i.e., CF related to the fuel usage). The economic cost of the fuel encompasses both stages and is part of the OPEX. Starting from the diesel fuel, the CF stemming from diesel production is estimated from [16] as 18.9 gCO_2/MJ; this value has been maintained constant across the different energy mixes, and also constant in the future. This hypothesis is attributed to the minimal electricity consumption in diesel production and the expectation that the petroleum refining and production processes will remain substantially unchanged in the future. An additional CF arises from diesel usage and the CO_2 emissions generated by the combustion.

Table 3
Summary of the considered data and sources for the TCO and LCA analysis, with relative references in brackets.

Item		ICEV	HEV	H2-HEV	FCEV	BEV
Glider	*LCA*			Not considered		
	TCO [k€]			200 [29]		
ICE	*LCA [kgCO_2/kW]*		13 [52]		–	–
	TCO [€/kW]		30 [36]		–	–
FC	*LCA [kgCO_2/kW]*		–		28 [24]	–
	TCO [€/kW]		–		440 [24]	–
E-motor	*LCA [kgCO_2/kW]*	–			3.6 [53]	
	TCO [€/kW]	–			10 [36,54]	
Inverter	*LCA [kgCO_2/kW]*	–			2.4 [55]	
	TCO [€/kW]	–			5 [36,54]	
H2-tank	*LCA [kgCO_2/kgH_2]*	–	–	280 [24]		–
	TCO [€/kgH_2]	–	–	500 [36]		–
Battery	*LCA [kgCO_2/kWh]*	–		80 [56]		135 [57]
	TCO [€/kWh]	–			200 [25]	

A different approach has been taken for compressed hydrogen. In this case, two different production pathways have been analyzed, modeling hydrogen production by SMR or via electrolysis by means of a PEM cell electrolyzer. This choice is justified by the fact that the former technology, which exploits methane as a primary source, requiring minimal electricity (i.e., 1.11 kWh of electricity and 165 MJ of methane for 1 kg of H_2), is today the industrial standard and the base benchmark in contrast with the substantial electricity-driven electrolysis process (i.e., 54.6 kWh for 1 kg of H_2), as detailed in Table 4.

These estimations come from [52] and have been used as input data for the hydrogen supply chains representation in openLCA [53], using the EF database from the Joint Research Center (JRC) [54]. The hydrogen production plant has been assumed to be located in the same country where hydrogen is utilized, considering a "domestic" production of the energy vector. In this particular case, the CF attributed to hydrogen transportation is considered negligible [55]. However, an additional footprint is considered for hydrogen compression, at the storage pressure of 700 bar, based on projections for this market segment [55]. From the cost point of view, due to the current state of distribution infrastructures, it is not feasible to differentiate hydrogen costs among various production chains. Therefore, an average price is assumed for European countries, with adjustments made to this parameter according to recent forecasts by IRENA [42], as done for diesel fuel and electricity (details summarized in Table 5). In particular, the production cost of hydrogen has been evaluated in the cited analysis [42] depending on different variables as the investment cost of electrolysers, their capacity factor and the cost of electricity (hydrogen from electrolysis), and on the price of natural gas (hydrogen from SMR). A sensitivity analysis on hydrogen price has been added, for selected European countries. The last considered energy vector is electricity, directly employed by the BEV with an external charge. Both in the current and future scenarios, to enable cross-country comparisons and evaluate the impact of regional price differences on the TCO, specific

Table 4
Resources required to produce 1 kg of H2 from different production technologies, data from [52].

	SMR	Electrolysis
Natural Gas [MJ/kgH2]	165	–
Electricity [kWh/kgH2]	1.11	54.6
Water [kg/kgH2]	21.9	18.0

Table 5
Considered energy vector prices in the different scenarios, following the projections in [42].

	Current scenario	Conservative 2030	Optimistic 2030
Hydrogen [€/kWh]	0.023 (≈10 €/kg)	0.016	0.009
Diesel [€/kWh]	0.012 (≈1.6 €/L)	0.015	0.012
Electricity [€/kWh]	0.300	0.210	0.120

examples from European countries are considered. The analysis focuses on deviations in energy carrier prices from the European average, based on data from [56–58]. Finally, average grid CIs are assessed for different European countries, starting from different sources [35,46], forecasting these values in the future. Additionally, Italian MEM is taken into account, as previously discussed (Section 2.3).

The TTW analysis relies on powertrain fuel consumption derived from the findings presented by the Authors in [37]. In their prior investigation, the same bus powertrain performance, on designated driving cycles, was assessed by means of proper numerical simulations. This process involved the development of an appropriate energy management strategy for the FC systems aimed at simultaneously minimizing fuel consumption and mitigating degradation. To provide comprehensive insights, the summarized energy consumption results are reported in Table 6. It is essential to account for the energy consumption of auxiliary components, which significantly influences total consumption in the HDV sector. This aspect is particularly pertinent for BEVs, wherein adverse weather conditions can substantially increase the energy consumption for cabin heating/cooling, consequently reducing driving range. In this analysis, for an initial technology-neutral comparison, the bus is presumed to operate at an external temperature of 15/20 °C, when the power absorbed from cabin conditioning and battery thermal management is minimal, thereby the BEV configuration is not disadvantaged. The Authors expanded this analysis by including an assessment of how different external ambient conditions can impact the energy consumption of the analyzed powertrains in [59]. A similar case study have been analyzed also in [60] with a variation of the HVAC power demand.

Another important aspect of an urban bus with a long lifetime pertains to the frequency of component replacements. In particular, the replacement of battery packs for Li-Ion batteries is recommended every 150–200,000 km, in the passenger car segment [61]. Considering high-capacity battery, typical of a fully electric city bus with a long expected lifetime, different replacements are assumed for the battery back, ranging from 1 to 5 [15,21]. Then, in this study, a single battery replacement is considered for smaller-capacity units in the HEV and FCEV powertrains, and two replacements are anticipated for the BEV along the bus lifetime. Instead, as the FCEV is concerned, the EoL for FC systems is established when the system efficiency reaches 40 % of its initial value [62]. Under this assumption, three replacements are needed for the FC stack on the MLTB driving cycle, while only two are required for the other two cycles. This result comes from the adopted energy management strategy, tailored to obtain a trade-off between consumption and FC lifetime [37]. Finally, maintenance data for ICEV, FCEV, and BEV powertrains are directly sourced from [33] (i.e., 0.35 €/km, 0.24 €/km, 0.21 €/km, respectively). For hybrid vehicles HEV and H2-HEV, a value slightly lower than that for ICEV is assumed (i.e., 0.33 €/km),

Table 6
Energy consumption of the different powertrains on the simulated driving cycles, obtained by the Authors in [37].

	Braunschweig	Gillingham	MLTB
ICEV [kWh/100 km]	364	415	398
HEV [kWh/100 km]	279	318	272
H2-HEV [kWh/100 km]	262	303	267
FCEV [kWh/100 km]	212	254	210
BEV [kWh/100 km]	114	128	122

considering reduced wear thanks to regenerative braking. The CF of ordinary maintenance is presumed to be relatively consistent across powertrain types (i.e., 32 gCO_2/km), obtained from [15].

3. Results

In this section, the results of various scenarios are presented. The first focus, as detailed in Fig. 5, is on the production and EoL phases for all the different powertrains. Subsequently, the environmental impact of the two production pathways for hydrogen is also reported. Furthermore, an assessment of the environmental and economic impacts is conducted on the entire bus lifetime, encompassing the different energy consumptions observed across the selected driving cycles. The analysis is then completed with a sensitivity on the main parameters, as described in Fig. 5, and a 2030 projection of the scenario. Finally, a case study focused on Italy is presented, assessing the influence of variations in the electricity generation mix on the LCA of powertrains.

3.1. Production and EoL phase

According to the findings of our analysis, the production phase holds limited significance in the overall life cycle of a public transport vehicle, especially when compared to that of a passenger car, mainly due to its longer lifespan. However, its importance increases notably when a fleet-wide replacement is planned. Fig. 6 presents the total embodied carbon emissions (left) and the CAPEX (right) for the different powertrains, obtained in the current scenario. The CF associated with glider production is excluded from the analysis, as it is common to all the powertrains and therefore does not influence the LCA comparison, but could not be avoided in the CAPEX analysis.

For what concerns the production stage, in terms of environmental impact, a clear trend emerges from the analysis: the higher the vehicle electrification, from the ICEV to the BEV, the higher the resulting CF. In addition, hydrogen powertrains (H2-HEV and FCEV) show a CF twice as much as diesel-fueled powertrains, primarily due to the contribution of carbon fiber tanks required for high-pressure hydrogen storage onboard (i.e., 8.3 tCO_2 for each vehicle for the whole H2-tanks system). A recycling process was also considered for the Platinum Group Metals (PGMs) within the FC stack, resulting in a 1 % overall reduction in the embodied emissions of this component. In addition, the high-capacity battery needed by the BEV is assumed to be produced in China (the current market leader), where the grid CI is notably high (i.e., 534 gCO_2/kWh in 2024), obtaining a total value for the high-capacity battery of 45.4 tCO_2 for the BEV. This value can be partially offset by considering the impact of the EoL process. In this case, the EoL exceeds the CF associated with recycling and waste disposal, resulting in a net impact of −2 tCO_2 for the BEV during the entire EoL phase. This contributes to an overall 4 % reduction in the carbon footprint of BEV production. Findings regarding embodied emissions align with those reported in existing literature, such as in [15], and a component-level breakdown analysis is reported in Appendix C. A similar situation is reflected in the CAPEX: the higher the level of electrification, the higher the cost of the powertrain.

3.2. Well-to-Tank: hydrogen production pathways

A comprehensive analysis of the WTT process is needed to characterize different pathways for hydrogen production and distribution, as mentioned in Section 2.3. The production facilities are assumed to be located near the final fleet utilization, leading to a limited CF associated with transportation and distribution. The primary technologies currently considered for hydrogen production are the SMR from methane and the electrolysis in PEMFC. These two processes are characterized by different electricity requirements, as shown in Table 4: a factor that significantly influences the CF of the produced hydrogen. In particular, Fig. 7 presents the CF related to the production, distribution, and compression to a final pressure of 700 bar of 1 kg of hydrogen for the

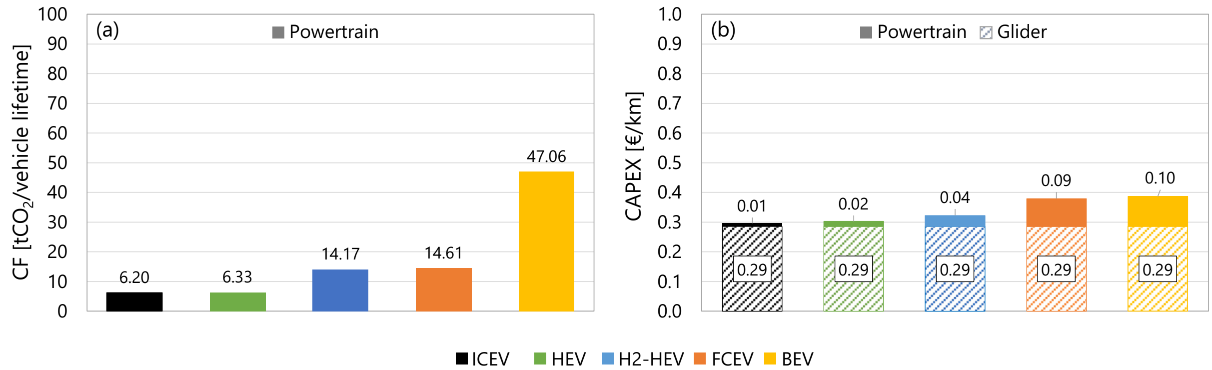

Fig. 6. Production phase analysis. (a) Embodied carbon emissions (glider excluded), (b) CAPEX (including the glider). The filled histograms refer to the values coming from the powertrain components, while the dashed ones refer to the glider.

SMR and the electrolysis process, as a function of the average CI for electricity generation.

Specifically, the considered renewable energy mix comprises 70 % hydro, 20 % wind, and 10 % solar, resulting in a grid CI of approximately 13.5 gCO_2/kWh. The considered mix is a limit case representing a small-scale local production fed by low impact renewable energies [63]. The French grid CI (i.e., 85 gCO_2/kWh) is noteworthy for its reliance on nuclear energy (accounting for 64 % of the total in 2024) and is one of the lowest CI among European countries. On the opposite, the Polish grid CI (i.e., 633 gCO_2/kWh) exemplifies a coal-based energy mix (constituting 70 % of the total in 2024), closely resembling the CI of Indian (i.e., 635 gCO_2/kWh) and near to the Chinese grids (i.e., 540 gCO_2/kWh). The Italian energy mix is mainly fossil-based, especially on gas-fired power plants (i.e., 50 % of the total in 2024), but with a notable share of renewable energy sources (close to 30 %) thus leading to a CI of 373 gCO_2/kWh. Currently, hydrogen produced via electrolysis can be deemed environmentally favorable only if sourced from electricity generated on grids with a significant proportion of renewable sources, qualifying as “green hydrogen”. Conversely, the hydrogen produced by SMR, so-called “grey hydrogen” is characterized by an almost constant CF, substantially independent from the grid CI, due to the small electricity input in the process and resulting in a lower CF with respect to hydrogen produced from electrolysis by the grid with CI higher than 200 gCO_2/kWh. For the sake of brevity, in this study, alternative production and transportation pathways are not considered, such as establishing hydrogen production plants in regions abundant with renewable resources (e.g., MENA countries), followed by transportation of liquefied hydrogen via pipelines or ships. It has already been demonstrated that these pathways may result in H_2 CF comparable to domestically sourced green hydrogen [55]. The present work has been expanded by the Authors in [59] by including the evaluation of SMR-produced hydrogen, adding carbon capture and sequestration techniques in the process.

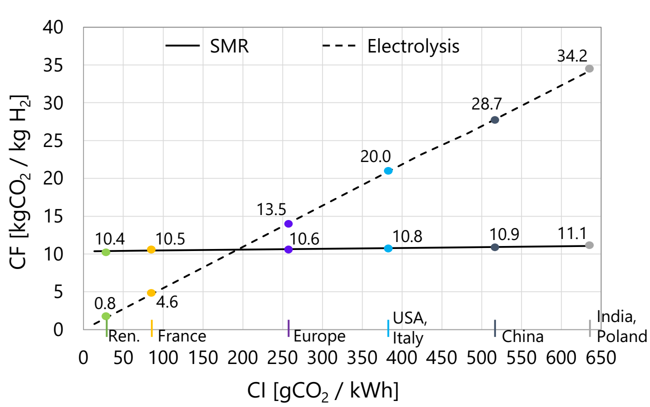

Fig. 7. WTT analysis for two different hydrogen production pathways as a function of the grid CI.

3.3. Powertrains life cycle

The comprehensive assessment of the environmental and economic impacts of various powertrains throughout the entire lifecycle of the vehicle involves the integration of data derived from multiple sources. These include the production phase (Section 3.1), the WTT emissions for different fuels (considering two production pathways for hydrogen in Section 2.2), the fuel consumption for the three different mission profiles, and the EoL phase. The results in terms of LCA, presented in Fig. 8, depict the total CF as a function of the average CI for electricity generation across the different mission profiles. The chosen FU is the quantity of equivalent CO_2 produced for km traveled (assuming a lifetime of 700.000 km).

In general, diesel powertrains are minimally influenced by the CI of electricity generation, as the majority of CF is related to the fuel combustion stage, resulting in a threshold used as a reference for the other powertrains. In particular, a common trend observed is a reduction in total CF when a hybrid configuration is considered, and so shifting from the ICEV (black lines) to the HEV (green lines). This counteractive trend compared to the production phase is attributed to the lower fuel consumption of HEVs, resulting in reduced CF during the use phase, which significantly impacts the overall lifecycle of urban buses with assumed extended operational lifespans. Regarding the hydrogen-fueled vehicles (orange and blue lines), the impact of the WTT stage results is evident. When hydrogen is produced via SMR, a relatively constant CF is observed across the entire range of grid CI, yielding similar patterns to the diesel powertrains. More in detail, when the FCEV is fueled by SMR-produced hydrogen (orange full lines) it becomes highly competitive with HEV, exhibiting lower CF across various mission profiles within the considered grid CI range. Moreover, the H2-HEV fueled by “grey hydrogen” (blue full lines) falls between ICEV and HEV. Conversely, when H2-HEV or FCEV are fueled by electrolysis-produced hydrogen, only green hydrogen emerges as a competitive option against HEVs, considering an average grid CI ranging from 0 and 200 gCO_2/kWh. Finally, the BEV emerges as the most competitive option in terms of environmental impact across a wide range of grid CI values.

Finally, the main trends seen among the bus architecture possibilities are similar across the different driving cycles. In particular, it is evident that adopting a more demanding driving cycle in terms of energy requirements and road gradient (i.e., Gillingham Fig. 8b) results in higher CF for all powertrain options. This is primarily due to the significant impact of the use phase, particularly fuel consumption, on the entire lifecycle, especially for public transport vehicles with assumed extended operational lifespans. For the sake of completeness, key results of Fig. 8a have been extracted and presented in Table 7, utilizing specified grid CI values for selected European countries. In this table, each row displays a colormap, with powertrains resulting in lower CF highlighted in green

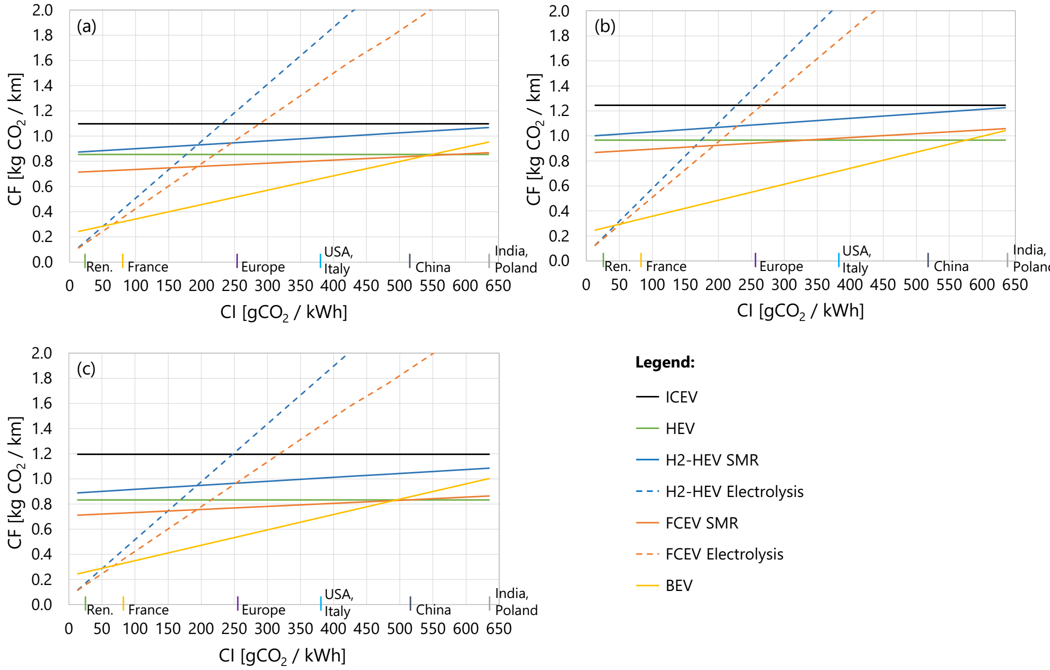

Fig. 8. LCA analysis as a function of the average grid CI, on the different driving cycles. (a) Braunschweig, (b) Gillingham, (c) MLTB.

and the one with the highest CF shown in red.

Data from Table 7, reveal several notable trends. In countries with a high share of renewable energy, particularly where the CI of the grid is below 150–200 gCO_2/kWh as in France, the CF of vehicles powered by hydrogen produced via electrolysis is comparable to, or even lower than, that of BEVs. As grid CI increases to an intermediate range (250–500 gCO_2/kWh), BEVs emerge as the most favorable option, while FCEVs powered by 'grey' hydrogen become competitive alternatives. Finally, when the grid CI exceeds 550 gCO_2/kWh, HEVs exhibit the lowest CF.

Additionally, the results based on the average CI of Europe are summarized in Fig. 9, including a breakdown of the various stages from production to EoL, along with detailed information on the TTW and WTT phases for each energy vector. As can be seen, the choice of energy vector plays a central role in determining the overall CF. For diesel-powered configurations, the embodied emissions from manufacturing are relatively minor over the vehicle's lifetime (i.e., less than 1 % of the total). In contrast, TTW emissions from diesel combustion are the dominant contributors, accounting for 72–73 % of the total CF in both

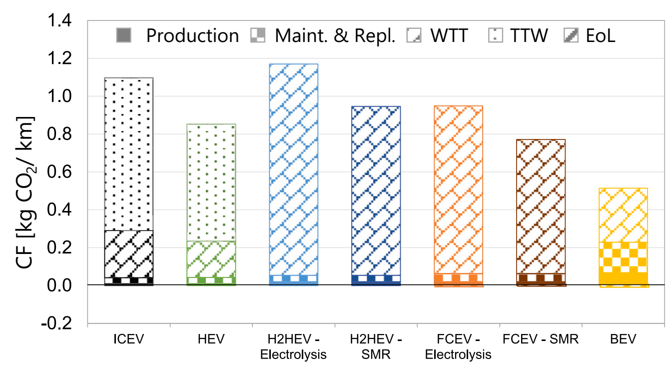

Fig. 9. Total lifecycle emissions of the different powertrains divided into embodied emissions (production), fuel production emissions (WTT), operational emissions (TTW), and EoL impacts, considering the average grid CI of Europe.

Table 7
LCA results on the Braunschweig driving cycles for given grid CIs, extracted from Fig. 8.

Mix	CI [gCO_2/kWh]	ICEV [$kgCO_2/km$]	HEV [$kgCO_2/km$]	H2-HEV [$kgCO_2/km$]		FCEV [$kgCO_2/km$]		BEV [$kgCO_2/km$]
				Electrol.	SMR	Electrol.	SMR	
Renewable	13.5	1.10	0.85	0.12	0.87	0.11	0.71	0.24
France	85	1.10	0.85	0.44	0.90	0.37	0.73	0.33
Europe	250	1.10	0.85	1.17	0.95	0.95	0.77	0.51
Italy/USA	373	1.10	0.85	1.72	0.99	1.39	0.80	0.65
Germany	420	1.10	0.85	1.97	1.00	1.59	0.82	0.71
China	533	1.10	0.85	2.43	1.04	1.95	0.84	0.84
Poland/India	633	1.10	0.85	2.88	1.07	2.31	0.87	0.95

ICEV and HEV options. For hydrogen-based powertrains, the primary impact arises from hydrogen production (WTT), with a notable reduction when SMR is employed instead of electrolysis, due to the considered mean European value of CI (i.e., 250 gCO_2/kWh). The BEV, on the other hand, shows a significant contribution from vehicle production and component replacement (45 % of the total), largely due to the high CF associated with current NMC battery technologies. The EoL phase contributes positively, as indicated by negative values in the chart, for both FCEVs and BEVs, although the effect remains relatively modest in the overall balance.

However, the market penetration of a given technology depends not only on its sustainability and decarbonization potential but also heavily on its economic viability. This consideration is particularly relevant when public strategies are involved, such as the partial or complete replacement of a bus fleet. To this end, the TCO of the different powertrains has been evaluated and presented in Fig. 10 for the considered driving cycles and with average values of energy vector prices around Europe (see Table 5). Notably, similar to the total LCA, the use phase (i.e., OPEX) significantly affects the final results. In addition, all powertrains exhibit a higher TCO in the Gillingham driving cycle, where fuel consumption is the highest.

Regarding the trend among the different powertrains, the HEV emerges as the option with the actual lowest TCO, followed by the BEV. This is due to its superior fuel economy compared to ICEV and the reduced cost of the downsized engine, which offsets the investment required for powertrain hybridization. On the other hand, hydrogen-fueled vehicles remain the most expensive option because of the current high cost of hydrogen, despite competitive CAPEX and efficient powertrains. It is also noteworthy that OPEX is significantly impacted for both FCEV and BEV due to the need for FC stack and battery replacements. Finally, while the BEV offers the best tailpipe carbon-free architecture, with higher efficiency and lower maintenance costs, its TCO is still slightly high when compared with the diesel HEV. Nevertheless, the results presented in Fig. 10 were obtained using fixed energy vector prices and averaged over the current European context. A further sensitivity analysis could be conducted to account for regional price variations and their impact on the TCO of different powertrains. In particular, hydrogen and electricity prices were differentiated based on the sources referenced in [56–58]. For selected European countries, the results of this analysis are presented in Table 8 with the same color code as Table 7. In the present context, the most economically advantageous powertrain is the HEV. However, in countries where electricity costs are around 0.25–0.28 €/kWh, such as the UK or France, the BEV can achieve cost parity with the HEV. Conversely, given the current hydrogen prices across Europe (ranging from 9 to 13.5 €/kg) and in the absence of policy incentives, both H2-HEV and FCEV remain less cost-competitive than the ICEV.

3.4. European context for clean bus alternatives in the future scenario

The reference scenario presented in Section 3.3 considers the actual situation in terms of grid CIs, fuel prices, market penetration, and the consequent high cost/impact of the emerging technologies. The trend of the above mentioned variables is the most difficult to forecast, with a possible large variability and influence on the results. For this reason, several sensitivity analyses have been performed regarding various data characterizing the production phase of emerging technologies, projections in terms of future grid CIs, and different levels of fuel prices. For the production phase, starting from the current situation with an assumed production of 200 units by OEMs for FC stacks, hydrogen tanks, and batteries, two scenarios for 2030 have been projected: a conservative scenario with 1000 units produced and an optimistic scenario with 20.000 units produced each year for OEMs, as detailed in Appendix B. Additionally, two fuel price levels for diesel, hydrogen, and electricity have been assumed for the 2030 scenarios, as shown in Table 5. In terms of fuel consumption, reference values of the Braunschweig driving cycle have been used (see Table 6). Fig. 11 presents an overview of the key results obtained for both the 2024 and 2030 time horizons, with the CF of each powertrain against the TCO. Consequently, the most cost-effective powertrain corresponds to the one located in the lower-left region of each graph. In the present scenario (Fig. 11a), a range of variability in the CF is highlighted, reflecting the impact of grid CI from

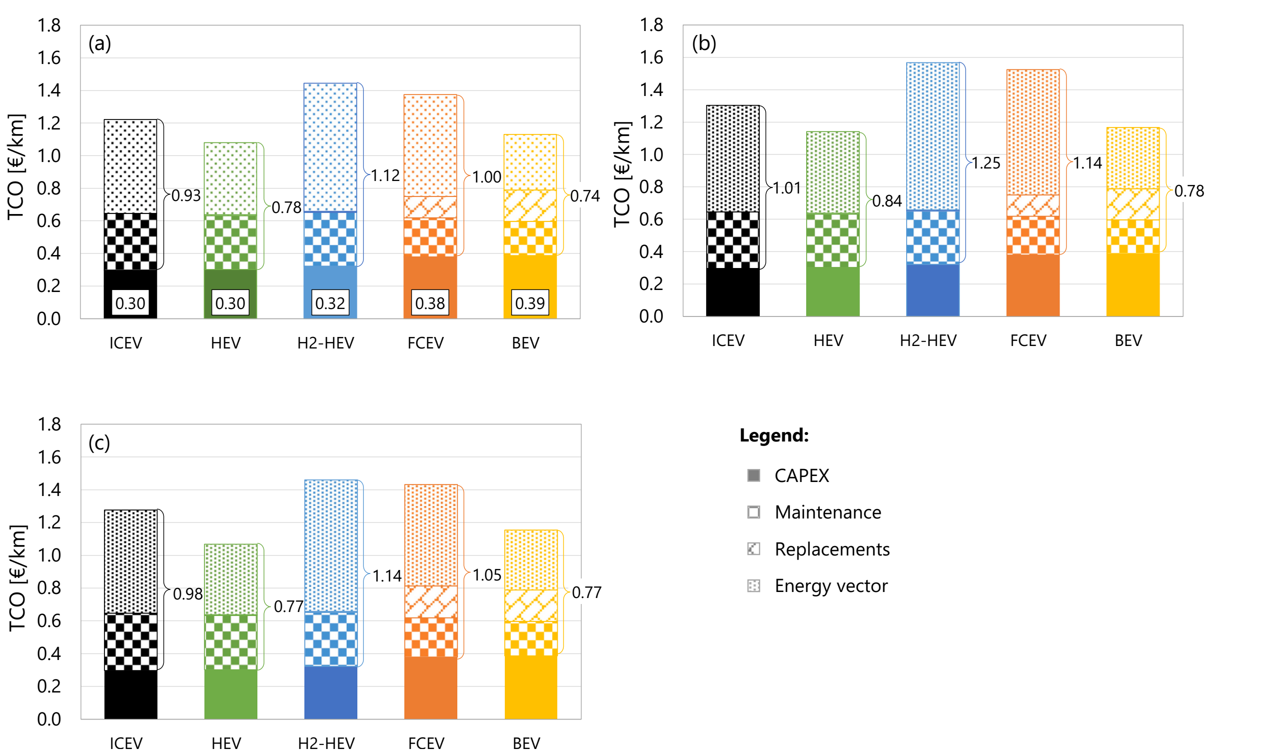

Fig. 10. CAPEX and OPEX (including maintenance, replacements and use) on the different driving cycles. (a) Braunschweig, (b) Gillingham, (c) MLTB.

Table 8
TCO results on the Braunschweig driving cycles for selected European countries.

	H_2 price [€/kgH_2]	Elec. price [€/kWh]	ICEV [€/km]	HEV [€/km]	H2-HEV [€/km]	FCEV [€/km]	BEV [€/km]
Europe	10	0.30	1.22	1.08	1.44	1.38	1.13
France	9	0.25	1.22	1.08	1.37	1.31	1.07
Italy	13.5	0.37	1.22	1.08	1.72	1.59	1.21
Germany	12	0.38	1.22	1.08	1.60	1.50	1.22
UK	10	0.28	1.22	1.08	1.44	1.38	1.10

a minimum value based on a completely renewable-based mix to the European maximum (currently Poland's energy mix), as analyzed in Fig. 8. For the 2030 scenario, two different forecasts, "optimistic" and "conservative", are considered, taking into account technology market penetration, energy vector prices, and grid CI, as summarized in Fig. 5. This results in a range (band on the graph) where the combination of CF and TCO could be drawn for the future, depending on the assumptions of the two scenarios and a combination of the uncertainties. All the points in the highlighted area result in possible future situations in terms of costs and environmental impact of the different powertrains. This also allows for mixed scenarios between the conservative and optimistic projections to be considered. The variability on the x-axis is mainly related to the costs of innovative technologies and energy vector prices. The variability on the y-axis is primarily related to the geographical location of powertrain usage and the consequent different projected grid CIs. Additionally, a specific analysis of selected European countries will be presented in Fig. 12.

Currently (Fig. 11a), the best compromise overall in terms of economic and environmental footprint is the HEV, while the BEV emerges as the best tailpipe carbon-free bus option, especially with grids featuring low CI. It is worth mentioning that the high variability in European grid CIs leads to a wide range of possible CFs for hydrogen powertrains. To achieve a competitive economic impact for the FCEV and the H2-HEV, enhanced market penetration of hydrogen-related technologies is pivotal. This is evident in the future scenario (Fig. 11b), where the FCEV has a broad range in which it results as the most economical option, also exhibiting a CF lower than diesel-fueled powertrains. The H2-HEV appears economically viable with respect to HEV only towards the optimistic scenario, due to higher fuel consumption compared to the FCEV, counterbalanced only in the case of very low hydrogen prices (e.g., 4 €/kg in the optimistic scenario). Regarding the BEV, it remains the best option in a conservative scenario, thanks to the limited variability of electricity prices and battery costs, which are already at a low level.

Additionally, the countries selected for the specific analysis in Tables 7 and 8 are revisited in Fig. 12, which combines different projections of grid CIs, energy vector prices, and the penetration of emerging technologies under both conservative and optimistic scenarios. Data for the production phase are taken from Appendix B, while details on energy vector prices and grid CIs for each scenario are provided in the inset boxes within the figure. In more detail, the projected grid CIs and electricity prices for each country's future scenarios follow the framework illustrated in Fig. 5. Regarding hydrogen cost, the conservative scenario assumes a reduction of €3/kgH_2 from the current level of each country, reflecting production costs driven by increased market penetration. The optimistic scenario projects a €6/kgH_2 decrease, further accounting for incentives resulting from policy investments [56]. Under these hypotheses, the analysis is also extended beyond the constraints of the European average TCO presented in Fig. 11.

As a general observation, the most cost-effective powertrains depend on the specific combination of variables considered, although the BEV emerges as the most favorable option in the majority of scenarios. In countries where the energy mix is predominantly based on renewables, such as France (Fig. 12a), the resulting low grid carbon intensity and hydrogen prices in the range of 3–6 €/kg make all "clean" bus alternatives highly competitive for replacing ICEV and/or HEV fleets. The cost-

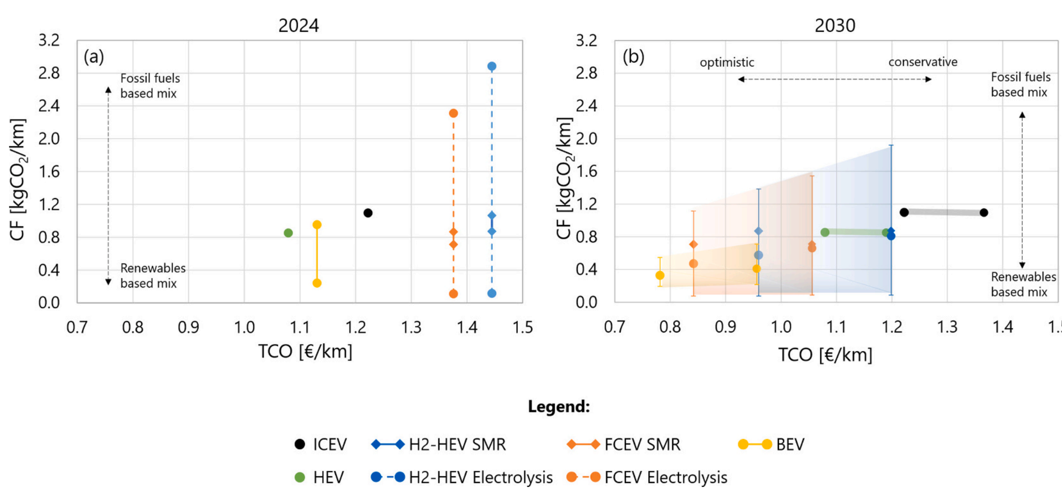

Fig. 11. Results summary in terms of LCA and TCO of the different powertrains in the two considered timeline scenarios for the European context: (a) 2024, (b) 2030, optimistic and conservative forecasts, with uncertainty bands. The data variability on the CF is related to the considered grid CIs, and the TCO is related to the cost scenario adopted, as highlighted by the black arrows.

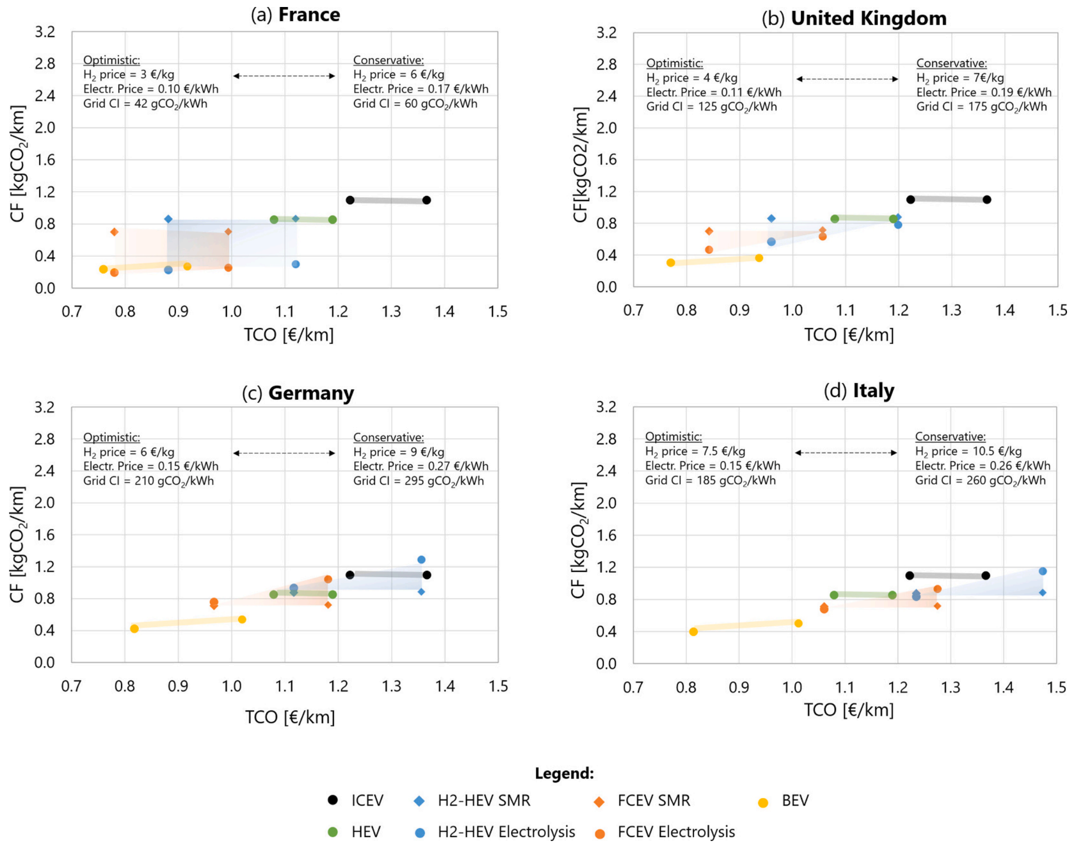

Fig. 12. Results summary in terms of LCA and TCO of the different powertrains in a future 2030 scenario, with optimistic and conservative forecasts, for specific European countries.

effective region for the BEV also overlaps with that of the FCEV. Additionally, if hydrogen is produced via grid electrolysis (orange circles), the CF of the FCEV can be even lower than that of the BEV. While the H2-HEV also exhibits a competitive cost frontier, its lower fuel efficiency makes it less advantageous than the FCEV. With increasing hydrogen prices and grid CI, as seen in the UK (Fig. 12b), hydrogen-fueled powertrains become less cost-effective; the H2-HEV, for instance, reaches cost parity with conventional HEV, although all "clean" alternatives still maintain a lower CF than diesel powertrains. A grid CI threshold of approximately 180–200 gCO_2/kWh marks the limit for hydrogen powertrains to achieve a CF lower than that of HEV. In a future scenario with hydrogen prices between 6 and 9 €/kg, as in Germany (Fig. 12c), the H2-HEV equals the TCO of the ICEV, while the FCEV matches that of the HEV, suggesting 6 €/kg as an upper limit for hydrogen cost viability. In addition, grid CIs higher than 250 gCO_2/kWh result in higher CF when hydrogen is produced by grid electrolysis, instead of grey hydrogen. The projected situation in Italy (Fig. 12d) is similar to Germany in terms of LCA, but higher hydrogen prices make the BEV the only cost-effective alternative for replacing conventional diesel fleets.

To conclude, an index has been defined to couple environmental and cost impacts: the cost of a powertrain has been divided by the corresponding CO_2 savings achieved compared to conventional diesel powertrains. In particular, for the i_{th} technology, the index is defined in Eq. (1):

$$\left[\frac{€}{\Delta kgCO_2}\right] = \frac{TCO_i\left[\frac{€}{km}\right]}{CF_{ICEV}\left[\frac{kgCO_2}{km}\right] - CF_i\left[\frac{kgCO_2}{km}\right]}. \tag{1}$$

It follows that, given the way the index is defined, the lower its value, the greater the economic and environmental benefits of the technology under consideration as a potential alternative to the ICEV. Table 9 presents the results in terms of cost for $kgCO_2$ saved with the introduction of a certain powertrain, for both the current scenario and the projected future scenarios, considering the minimum grid CI value (representing a renewable energy mix) and the maximum European grid CI value (representing a coal-based energy mix). The negative values (i. e., when ICEV exhibits lower environmental impact than tailpipe carbon-free options) are not listed in the table, because out of the scope of the comparison. The same color code of Table 7 is employed.

From the first three rows of Table 9, H2-fueled powertrains and BEVs represent the most economically viable options for decarbonizing the urban transport sector, provided that the associated energy vectors are produced using near-renewable energy mixes. Under future projections, FCEVs using green hydrogen show lower costs than BEVs, with cost parity reached at a hydrogen price of 4.5 €/kg for an electricity price of 0.12 €/kWh. In the current scenario, the higher the CI of the grid, the more cost-effective the HEV, with a viability threshold for BEVs at around 500–550 gCO_2/kWh, (from fourth row of Table 9). In future scenarios with high grid CIs (last two rows of Table 9), BEVs remain the most cost-effective alternative for replacing conventional ICEVs. FCEVs supplied by SMR are competitive with BEVs only when hydrogen is priced around 4.5 €/kg for an electricity price at approximately 0.20 €/kWh.

3.5. Impact of marginal electricity mix: an Italian case study

The final sensitivity analysis evaluates the impact of varying assumptions regarding the CI of the electricity grid. Notably, all scenarios consider only the AEMs of the respective countries, even though these may not fully reflect the actual carbon emissions associated with the electricity grids. This study is located in Italy, a European country with a high availability of renewable energy sources, and with a high seasonal variability of the grid CI. Future works will also include a dedicated

Table 9
Cost of $kgCO_2$ saved by substituting a conventional ICEV bus with an alternative powertrain.

Mix	CI [gCO_2/kWh]	H_2 price [€/kgH_2]	El. price [€/kWh]	Scenario	HEV [€/ΔkgCO_2]	H2-HEV [€/ΔkgCO_2] Electr.	H2-HEV SMR	FCEV [€/ΔkgCO_2] Electr.	FCEV SMR	BEV [€/ΔkgCO_2]
Renewable	13.5	10	0.30	2024	4.42	1.47	6.44	1.40	3.58	1.33
	9.5	7	0.21	Cons. 2030	4.87	1.19	5.07	1.04	2.67	1.08
	6.8	4	0.12	Opt. 2030	4.42	0.94	4.03	0.82	2.11	0.86
Max CI EU	633	10	0.30	2024	4.42	-	47.10	-	5.98	7.81
	443	7	0.21	Cons. 2030	4.87	-	6.04	-	2.88	2.47
	315	4	0.12	Opt. 2030	4.42	-	4.55	-	2.23	1.42

analysis of this crucial aspect for other European countries. Fig. 13a shows an example of the hourly variability of the grid CI on a spring day of March 2024, a month when the renewable energy availability starts to rise, with respect to the winter season. It could be seen that a difference accounts for more than 100 gCO_2/kWh, between the night CI (e.g., 352 gCO_2/kWh at 23:00) and the day (e.g., 239 gCO_2/kWh at 13:00). Consequently, the mean CI for this March day is 308 gCO_2/kWh, in contrast to the AEM of 373 gCO_2/kWh over the entire year. Another critical aspect to consider is the role of marginal power plants in electricity production. When electricity is generated at night or additional loads are requested from the grid, marginal plants, typically fossil fuel-based, are used. This aspect is of paramount importance when including the BEV in the analysis, assuming overnight charging. This reliance on marginal plants can significantly increase carbon emissions, potentially leading to substantial miscalculations of the transport sector's CF [22]. The considered input data for Italy for the MEM is 590 gCO_2/kWh [47]. In summary, Fig. 13b presents the total CF of the different clean bus architectures, comparing different grid CI: the AEM, the hourly mix on the day of Fig. 13a with the span for night/day, and the MEM.

The considered variation in the electricity mix highly influences the results, except for hydrogen powertrains fueled by "grey hydrogen", thanks to the low percentage of electricity used in the process. Observing the first column of each group (typical March day mix), it shows that when hydrogen is produced by electrolysis, a significant improvement is evident as the share of renewable energy in the mix increases. This results in a competitive CF for the FCEV if hydrogen is produced by electrolysis during the day. Conversely, if the electrolyzer operates during periods of extra load (third column of each group), relying on marginal plants, the resulting CF could potentially double. Furthermore, the CF of a BEV recharged using the MEM is comparable to that of the H2-HEV and is higher than that of the FCEV, both of which are fueled by hydrogen produced through SMR. This underscores the necessity for precise temporal, geographical, and fuel production pathway localization of all considered processes in an LCA. In addition, accurate data regarding grid CI is crucial to producing meaningful results. Some of these aspects are addressed in the last European Delegated Act on Hydrogen production [64]. This concept may play a crucial role in the actual deployment of hydrogen-based value chains.

4. Conclusions

This study evaluates the potential of hydrogen-fueled and electrified powertrains to decarbonize public transport by analyzing both environmental and cost impacts. Three tailpipe carbon-free bus alternatives, a Fuel Cell Electric Vehicle (FCEV), a Hybrid Electric Vehicle (HEV) powered by a hydrogen Internal Combustion Engine (H2-HEV), and a Battery Electric Vehicle (BEV),were assessed against a hybrid diesel bus (HEV) and a conventional diesel vehicle (ICEV) over their full life cycle. The main findings of the work can be summarized as follows:

- Current viability of electrified and hydrogen-powered vehicles: at present, when powered by renewable energy sources, all alternative powertrains exhibit CO_2 abatement costs competitive with HEVs. However, if grid Carbon Intensity (CI) exceeds the EU average (i.e., CI > 500 gCO_2/kWh), HEVs remain the most cost-effective option for CO_2 reduction.
- Optimistic future scenario: the FCEV exhibits the most promising trade-off in terms of economic and environmental impact, especially if hydrogen cost falls to 4€/kg and for a grid CI lower than 100 gCO_2/kWh.
- Conservative future scenario: with an intermediate penetration of hydrogen-related technologies in the market, BEVs emerge as the most cost-effective option for CO_2 reduction, even under high grid carbon intensities and for an electricity price lower than 0.25 €/kWh.
- Impact of marginal electricity mix: considering this mix for hydrogen or electricity production, the environmental impact of BEVs and

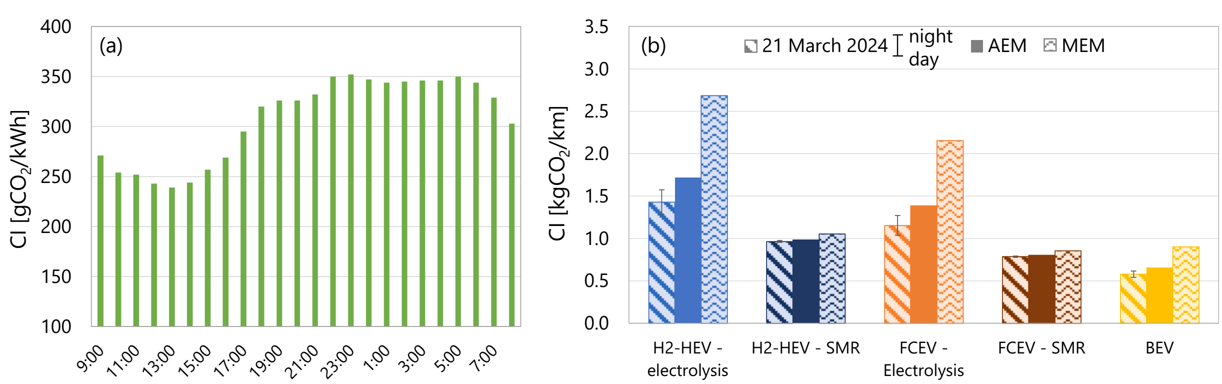

Fig. 13. (a) Hourly variability of the grid carbon intensity on a day of March in Italy. (b) LCA analysis considering hourly, average, and MEM in Italy.

hydrogen-fueled vehicles becomes comparable, particularly in cases like the Italian grid.

This study highlights the importance of a detailed characterization of the considered application coupling LCA and TCO analyses within real geographical contexts, typical driving cycles, and technology market penetration, to provide meaningful insights for planning and policy-making. Future research should explore seasonal variations in energy demand for heating, battery management, and auxiliary systems, as well as real-world performance data from operational FCEV and BEV fleets.

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CRediT authorship contribution statement

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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.

Appendix A. Technical specifications of the vehicle components

The powertrain configurations considered in this study are outlined below, with a summary of their main component specifications provided in Table 10A:

a) ICEV: diesel internal combustion engine vehicle
b) HEV: series hybrid electric vehicle with diesel ICE as APU
c) H2-HEV: series hybrid electric vehicle with hydrogen ICE as APU
d) FCEV: series hybrid fuel cell electric vehicle with PEM-FC as APU
e) BEV: battery electric vehicle.

Table 10A
Vehicle components technical specifications.

	Configurations	ICEV	HEV	H2-HEV
ICE	Fuel [–]	Diesel	Diesel	Hydrogen
	Displacement [L]	6.5	3.0	3.0
	Max. Power [kW]	250	100	100
	Source [–]	[40]	[40]	[40]
	Configurations	**FCEV**		
PEM FC	Fuel [–]	hydrogen		
	Net Power [kW]	100		
	Number of cells [–]	270		
	Source [–]	[65]		
	Configurations	**HEV/H2-HEV**	**HEV/H2-HEV/FCEV/BEV**	
		E-Generator	*E-traction*	
Electric motors	Technology [–]	PMSM	PMSM	
	Max Power [kW]	90	200	
	Max Torque [Nm]	440	1500	
	Source [–]	[66]	[67]	
	Configurations	**HEV/H2-HEV/FCEV**		**BEV**
HV Battery	Technology [–]	$LiFePO_4$		NMC
	Capacity [kWh]	20		336
	Arrangement [–]	120s20p		108s9p
	Source [–]	[68]		[69]
	Configurations	**H2-HEV/FCEV**		
Hydrogen tank	Technology [–]	Carbon fiber tank		
	Capacity [kg]	28		
	Pressure [bar]	700		
	Source [–]	[70]		

The worldwide bus fleets are still dominated by vehicles propelled by diesel ICE, hence, a conventional large-displacement ICE (6.5 L) diesel vehicle has been selected as a benchmark. In addition, a diesel series hybrid is considered, featuring a medium displacement diesel ICE (3.0 L) as Auxiliary Power Unit (APU), therefore resulting downsized with respect to the reference engine. In this configuration, the main power actuator is a 200 kW Permanent Magnet (PM) electric motor. It is worth noting that the electrified bus market predominantly favors PM motors, aligning with the trend observed in the light-duty hybrid vehicle industry, which is progressively shifting towards this technology [71], instead of induction machines. A 20 kWh Li-Ion battery was chosen to power the hybrid configuration [38]. Within the automotive sector, Li-ion-based chemistries are today predominantly used, primarily including Lithium Titanium Oxide (LTO), Lithium iron Phosphate (LFP), and lithium Nickel Manganese Cobalt oxide (NMC). LTO batteries offer the highest charging power, whereas NMC provides the highest energy density, albeit with the shortest cycle life among the three options [72]. Finally, LFP batteries present characteristics falling in between LTO and NMC in terms of energy density and lifetime, although their typical low charging power restricts fast charging capabilities [28]. Consequently, the versatility of LFP technology makes it suitable for utilization in small battery packs, while NMC has emerged as the preferred option for fully electric vehicles equipped with larger battery packs and extended driving ranges. Based on these reasons, for the present study, an LFP battery has been chosen for the hybrid series configurations, with cell specifications obtained from [68].

For H2-fueled powertrains and BEVs, the energy storage system has been sized to support a daily mission of approximately 200 km. This ensures that the bus requires only an overnight recharge at the depot for the BEV [31] and no refueling during the daily mission for the H2-fuelled vehicles. In addition, a warm external temperature has been hypothesized ($T_{ext} = 15/20$ °C), with the requirement of ventilation only to grant cabin comfort and no need for battery conditioning, for a first comparison in technology-neutral external conditions. Future works will assess also the impact of cabin and battery conditioning on BEV consumption. A third configuration has been defined (H2-ICE), which includes the same electric motor and battery setup as the HEV and replaces the conventional ICE with a Hydrogen ICE acting as the APU. The displacement of the ICE remains consistent with that of the HEV, and the engine's configuration suitable for hydrogen combustion characteristics has been obtained through retrofitting from the reference diesel engine; this solution offers the capability of providing the same rated power and minimizes the retrofit cost and complexity levels [73]. For the two-hybrid configurations featuring an ICE, an additional EM and AC/DC converter are required to feed electric energy to the on-board net.

Furthermore, the fourth presented configuration exploits again hydrogen as an energy vector, through a Proton Exchange Membrane (PEM) FC based APU (FCEV). A real FC system, comprehensive of all the auxiliaries (i.e. the air compressor and the humidifier) has been considered in the study to achieve the whole Balance Of Plant (BoP). The FC stack was rescaled to target a power level for the APU matching the other two hybrid architectures [65]. In both hydrogen-fueled powertrains, the same type of tank was chosen, storing gaseous hydrogen at 700 bar in a type IV tank, which currently is the most popular technology for H2-buses and heavy duty vehicles demo and prototypes [36,55,70], with an overall capacity of 28 kg of H_2 to cover the bus's daily mission without refueling.

The last powertrain configuration under consideration is a fully electric vehicle (BEV - Fig. 1b). The choice of this alternative stems from the increasing share of this technology in urban markets. In this case, the power actuator is an electric motor with 200 kW of maximum power. Moreover, a different battery chemistry, namely NMC, was selected for the HV battery, in contrast to the hybrid configurations. This selection is motivated by its high energy density, capable of fulfilling the vehicle range requirement. The key specifications of the battery cells were sourced from [69]. The battery capacity size aimed to avoid the need for recharging throughout a typical bus day mission and was based on an average capacity for 12-m urban buses: 336 kWh in line with the values commonly found in the literature for BEV buses [31,74].

Appendix B. Details of CAPEX data for the different scenarios in 2030

Two scenarios for 2030 have been projected, considering different penetration of hydrogen-related technology and batteries in the transport sector market, as summarized in Table 11A.

Table 11A
Inputs for the sensitivity analysis on market penetration for hydrogen-related technologies and battery cost.

Variable	Optimistic	Conservative
Number of units sold per year	20.000	1000
FC stack cost [€/kWh]	100	155
H2 tank cost [€/kg]	175	250
NMC battery cost [€/kWh]	100	150

Following this hypothesis, TCO results in terms of total CAPEX are presented in Fig. 14 for the hydrogen-fuelled powertrains and the BEV. The results are compared with the ones of conventional diesel powertrains as a benchmark, considered constant in future projections. The BEV exhibits the higher total CAPEX in all the scenarios, affected by the cost related to the need of a high-capacity battery. According to Bloomberg surveys, the average price of batteries in 2020 dropped to one-tenth with respect to their 2010 price, with a projected decrease rate of 15–18 % for the future (2030 scenarios) [6]. Consequently, in the optimistic scenario, the BEV is projected to decrease its gap with the other powertrains, in terms of CAPEX. For hydrogen-fueled technologies, competitiveness with diesel powertrains is reached only if significant market penetration is ensured, leading to reductions in FC and H2-tank production.

Fig. 14. TCO of the different powertrains considering different market penetration technologies, in comparison with diesel conventional powertrains.

Appendix C. Details of data acquisitions for the production and EoL phase from the literature

Regarding the production and maintenance phases of the different powertrains, no primary data were available: environmental and economic costs were therefore obtained by properly scaling literature data to fit the current case study, and have been reported in the text in Table 3. As previously mentioned, the glider serves as a common component for all powertrains and falls outside the scope of the LCA comparative analysis. Indeed, all the variations in vehicle weight primarily arise from differences in powertrain components, such as hydrogen tanks or batteries. The estimated cost for the glider averages 200 k€ based on an analysis in [29], where the cost for a 12-m e-bus ranges from 235 k€ to 420 k€ excluding only the battery. This value has been included in the TCO, because of its importance in the scope of policy making. Regarding the power units, the CF associated to the production of a thermal engine is deemed comparable between a diesel and a hydrogen engine, thanks to the similar components and manufacturing. It is noted that the materials used in a diesel combustion chamber already exhibit good resistance to the phenomenon of embrittlement, which is typical of hydrogen combustion [75]. The CF value is derived from a complete scalable LCA analysis, performed by Wolff et al. [76] for heavy-duty trucks, and is set therefore to 13 $kgCO_2/kW$ for both the diesel and the H2 ICEs. Regarding the FCEV, a comprehensive CF of the FC stack and the relative Balance of Plant (BoP) is obtained from [24], with an actual value of 28 $kgCO_2/kW$, considering a current production rate of 200 units per OEM. This value is subject to reassessment in sensitivity analysis, wherein it will be adjusted to different forecasts of market penetration in 2030. These forecasts consider 1000 units sold per OEM in a conservative scenario and 20,000 units sold in an optimistic scenario. The impact of the exhaust aftertreatment system is considered similar for hydrogen and diesel ICE, necessitating Selective Catalytic Reduction (SCR) to mitigate NOx emissions from hydrogen combustion, and it is estimated as 7 $kgCO_2/kW_{ICE}$ from [76]. From the cost side, a mid-sized diesel combustion engine, including transmission, is estimated at €30/kW, inclusive of exhaust treatment [36]. For the H2-HEV, given the current lack of mass production of hydrogen engines, their costs are estimated starting from the fact that the basic components closely resemble those of a diesel engine, including the EGR system. In this context, a company specializing in H2-ICE asserts that total costs and weight will approximate those of a diesel engine [77]. For the FCEV, the actual cost of the stack, comprehensive of the relative BoP, is derived from [24] reflecting a current scenario with 200 units sold per OEM. As mentioned before, this value will be projected in future scenarios. All the powertrains, except for the ICEV, require an e-motor and an inverter. Their CF is sourced from specific inventories for a PM traction motor [78] and automotive power electronic inverter unit [79]. The costs of these electric components are averaged from [36,80]. Furthermore, essential components for hydrogen-fueled powertrains are the storage tanks. In particular, hydrogen is considered to be stored onboard at 700 bar in a type IV carbon fiber tank, where a full 120-l tank could store approximately 5.6 kg of H_2. For the present application, five tanks have been chosen to store a total of 28 kg of hydrogen onboard, aiming to cover at least an urban bus daily range and aligning with current strategies of packaging [81]. The current price and CF from the production of carbon fiber remains high (see [36]), but is expected to decrease with the penetration of this technology, along with advancements in carbon fiber production [24]. Consequently, this parameter is among the focal points of the sensitivity analysis.

The final critical components to be taken into account are the batteries: the low-capacity LFP for the hybrid configurations, and the large-capacity NMC for the BEV. A large variability is present in the literature about the CF and the cost of batteries for the automotive sector [82]. These factors yield significant influence, particularly on the production phase of BEVs [61], and exhibit a decreasing trend as the technology becomes more widely adopted [26]. Different values have been considered for the CF of small-size LFP batteries [82] and large-size NMC batteries [83], as the impact is not always directly scalable with battery size. The geographical location of battery production holds paramount importance due to the substantial electricity consumption associated with battery manufacturing, and the consequent high dependency on grid CI [84]. For this study, China has been considered as the production location, given its status as the world's leading battery manufacturer [85]. Recent studies from Bloomberg [25] have provided updated average prices for lithium-ion batteries, divided by application, ranging from passenger cars to *E*-buses, thus confirming a significant variability on this parameter [28]. In this case, an average price has been considered for the LFP and the NMC batteries, with the battery price being updated in future forecasts across various selected scenarios [29]. A summary of the final values for the LCA analysis of the embodied carbon with component-level breakdown for the different powertrains is presented in Fig. 15.

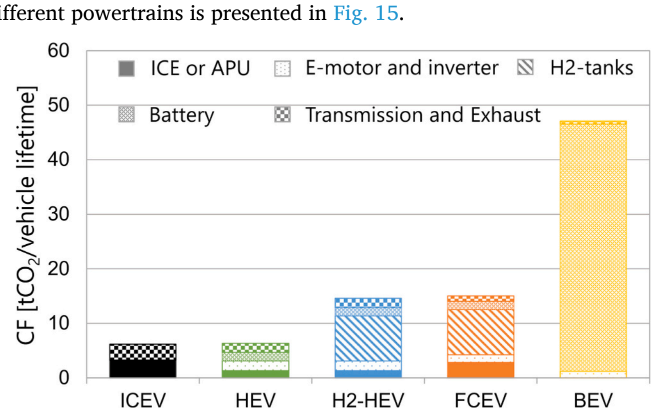

Fig. 15. Component-level breakdown for the embodied carbon emissions of the different powertrains.

For the EoL phase, two main approaches are present in the literature [86]:

- the avoided burden approach, which assigns environmental credits to secondary materials based on their potential to substitute primary materials, thereby accounting for the benefits of future recycling.
- the cut-off approach, which allocates the full environmental burden of waste treatment to the primary user, without assigning any credits for recycling or beneficial by-products.

For a fair comparison, the first approach has been adopted in the present study for the components that are generally primary contributors to environmental impacts in the production phase (i.e., the BEV's battery and the FC stack). With this approach, the battery EoL process can be divided into three key stages: recycling, which involves the energy-intensive treatment of battery materials and contributes to additional carbon emissions; credits, which reflect the environmental benefits from substituting virgin materials with recovered ones; and further waste disposal, addressing the treatment of non-recyclable residues. While recycling increases the GWP at the cell level due to energy demands, it leads to a net reduction in GWP at the battery-pack level. Overall, Accardo et al. [83] demonstrated that for an NMC battery EoL management results in an approximate 3/4 % improvement in the battery's total GWP impact, and a total value for the NMC battery EoL of −6.19 kg CO_2 / kWh has been accounted for in the present study.

Additionally, similar considerations could be done for PEMFC, especially concerning the recovery of PGMs. Notably, recycling of PGM materials in PEMFC can lead to a reduction of up to 16.1 % with respect to the GWP of the PGM materials production [87].

Data availability

Data will be made available on request.

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