



## Multi-Criteria Life-Cycle Assessment of bus fleet renewal: A methodology with a case study from Italy

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### ABSTRACT

To decarbonize the transport sector, national and local government have introduced policies to incentivize the replacement of old diesel-powered vehicles with new clean-fuel ones (e.g., battery electric, hydrogen fuel-cells). This paper focuses on both the economic and ecological transition of local public transit (LPT) bus fleets. A methodology based on a Life-Cycle Assessment (LCA) approach of both costs and environmental impacts is proposed to identify suitable pathways for the renewal of the existing buses: these are compared using a multicriteria decision matrix. The application to the Italian basin of the provinces of Como, Lecco and Varese (with about 860 operating buses almost all equipped with diesel engines) has allowed to validate the approach for both the urban and the ex-urban context. In the urban context, the study has shown that the full-electric scenario has the lowest environmental impact since there are zero tailpipe emissions and greenhouse gases (GHG) are lower than all the other scenarios. For the ex-urban service, that is characterized by medium and long-distance routes, a “full-electric” scenario is not yet feasible, considering that long-range BEBs having sufficient battery autonomy to guarantee efficient operations on medium-long distance routes are not yet widely marketed. Liquefied natural gas-powered buses could be a suitable solution in these contexts, however it was found that they have even worse environmental performances compared to diesel buses (+14% GHG emissions and more than doubled direct emissions). Hybrid electric vehicles would be an option for decarbonising ex-urban LPT, but the costs of the transition in such direction should be considered with care.

### 1. Introduction

Starting from the 21th United Nations Climate Change Conference of Parties hosted in Paris in 2015, world leaders committed to step up the efforts to contrast the impacts of climate change and to consistently invest resources in pathways towards low Greenhouse Gases (GHG) emissions and climate-resilient development (United Nations, 2015). Particularly, the adoption of the Paris Agreement requires countries to articulate both near and long-term low-emission strategies, updating, starting from 2020, every five years their Nationally Determined Contributions (NDCs) to demonstrate their progressive commitment towards decarbonisation (Iyer et al., 2017). Among the key policy priorities to foster the Paris Agreement objectives the decarbonisation of the transport sector has been identified as crucial (Tagliapietra et al., 2019). Indeed, in 2020 the European GHG emissions related to transport

amounted to 32% of the total, or in absolute terms, 889 million tons of equivalent CO<sub>2</sub>, second only to the energy sector. In detail, the 77% of the abovementioned emissions are related to road transport (Statistical Pocketbook, 2022). Considering land transport, passenger cars are the predominant transport mode with reference to passenger-km travelled (almost 86% of the total) while buses and coaches account for 7% of it. In terms of GHG emissions, private cars are responsible for almost 46% of the overall transport emissions while heavy-duty vehicles, buses and coaches account for 22% of those emissions. In addition, transport sector is also responsible for the emission of local pollutants such as NO<sub>x</sub>, CO and particulate matter (PM): despite the decreasing trend of such emissions, road transport local air pollution is exacerbated by heavy-duty trucks and buses emissions contributing to the NO<sub>x</sub> road transport emission by 34%, to CO by 7% and to 11% of PM<sub>2.5</sub> emissions (Air pollutant emissions data viewer (Gothenburg Protocol, LRTAP

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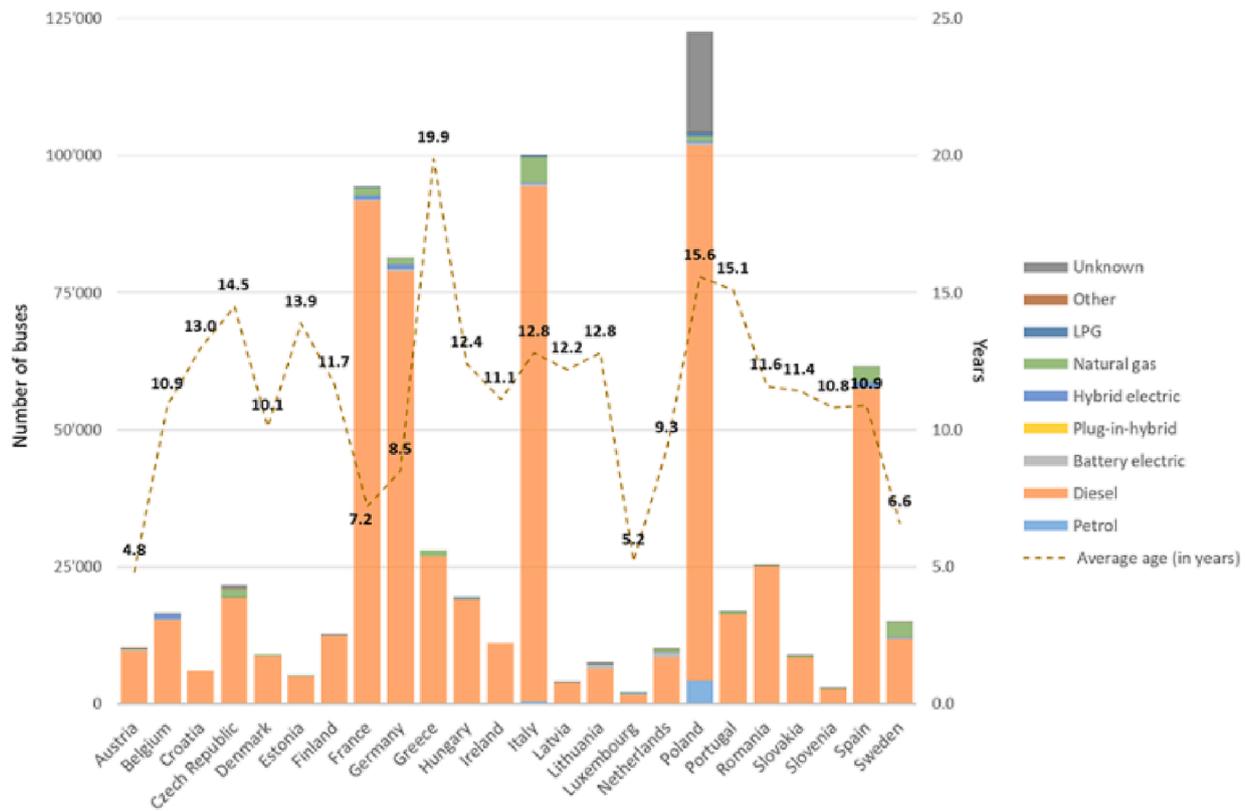


Fig. 1. European bus fleet classified by Member State, according to the engine type and average age. Elab. on data from (ACEA, 2021).

Convention), 2023).

Global and local pollution issues are mainly due to the diffusion of diesel internal combustion engine powertrain in heavy-duty segments. The situation is worsened by the relatively high average fleet age that reaches 12.8 years in Europe in case of buses, with only 6 countries showing values lower than 10 years (see Fig. 1).

To achieve a carbon-neutral economy by 2050 (European Commission, 2018), the European Commission introduced in 2019 and confirmed in 2020 during and despite the COVID-19 pandemic, the European Green Deal plan (European Commission, 2019), a set of policy initiatives to accelerate the transition towards a sustainable development. Among these, the progressive step to subsidies for fossil-fuel vehicles and the revision of the Energy Taxation Directive: the objectives are to discourage purchases and to encourage disposals of the most polluting vehicles at the same time. In this sense, the European Directive 2019/1161 takes actions in the public procurement fields in order to set minimum procurement targets for the percentage share of new clean vehicles (European Parliament, 2019), where the adjective “clean” refers to vehicles using alternative fuels, including electric, hydrogen, biofuel, synthetic and paraffinic, natural gas (both in gaseous and liquefied form) and liquefied petroleum gas powered vehicles (European Parliament, 2014).

The picture portrayed in this introduction highlights the need for disposing of effective methodologies to inform and support policy makers about possible future scenarios in which road transport vehicles are renewed in compliance with current European directives. The sole economic indicators fall short to address this issue, so additional life-cycle environmental performance indices are introduced. Focusing on bus fleet renewal, this study provides a life-cycle multi-criteria (i.e., economic, and environmental) dashboard able to support Local Public Transit (LPT) agencies in their energy transition policies. This paper contributes to the existing literature by discussing results from the application to a peculiar case study, covering a wide area composed of three Italian provinces, characterized by both urban and ex-urban LPT

service and whose current fleet is almost entirely diesel-powered.

The manuscript is organized as follows. After this brief introduction, in Section 2 a literature review on methodologies to assess bus fleet renewal is presented. The proposed method is described in Section 3 and is then subsequently applied in Section 4 to the case of a LPT agency of the provinces of Como, Lecco and Varese (Northern Italy): the aim is to identify sustainable scenarios with both a mid-term (2025) and long-term (2033) perspective. Results are discussed in Section 5, while conclusions are finally drawn in Section 6.

## 2. Literature review

Fleet renewal policy choices towards new clean-fuel vehicles are complex as the system they will influence is itself complex. Among the most challenging elements, there is the variety of dimensions that the decision-making process must encompass: for instance, the presence of different (and often conflicting) interests of decision makers and stakeholders, or the different objectives to be achieved with single choices. Tools to cope with the complexity of fleet renewal ex-ante assessment are mathematical methods and, according to what have been proposed in the literature, they can be clustered in a binary taxonomy: those based on a single-dimension or based on a multiple-dimension choice.

As far as the first category, in most studies the single-dimension choice is represented by the life-cycle cost (LCC) associated to the different vehicle alternatives. LCC is an overall esteem based on purchase, operating and maintenance costs, as well as the residual value of the vehicles to be included at the end of the analysis time span. With reference to both different types of power trains and/or different type of charging infrastructures, these cost items have been extensively comparatively analyzed (Comello et al., 2021; Krelling and Badami, 2020; Bi et al., 2017; Tong et al., 2017; Delucchi et al., 2010) and many studies address the problem of cost minimization, proposing optimization models to support the decision making process (for instance, (Ercan et al., 2015)). According to fleet characteristics, optimisation tools can

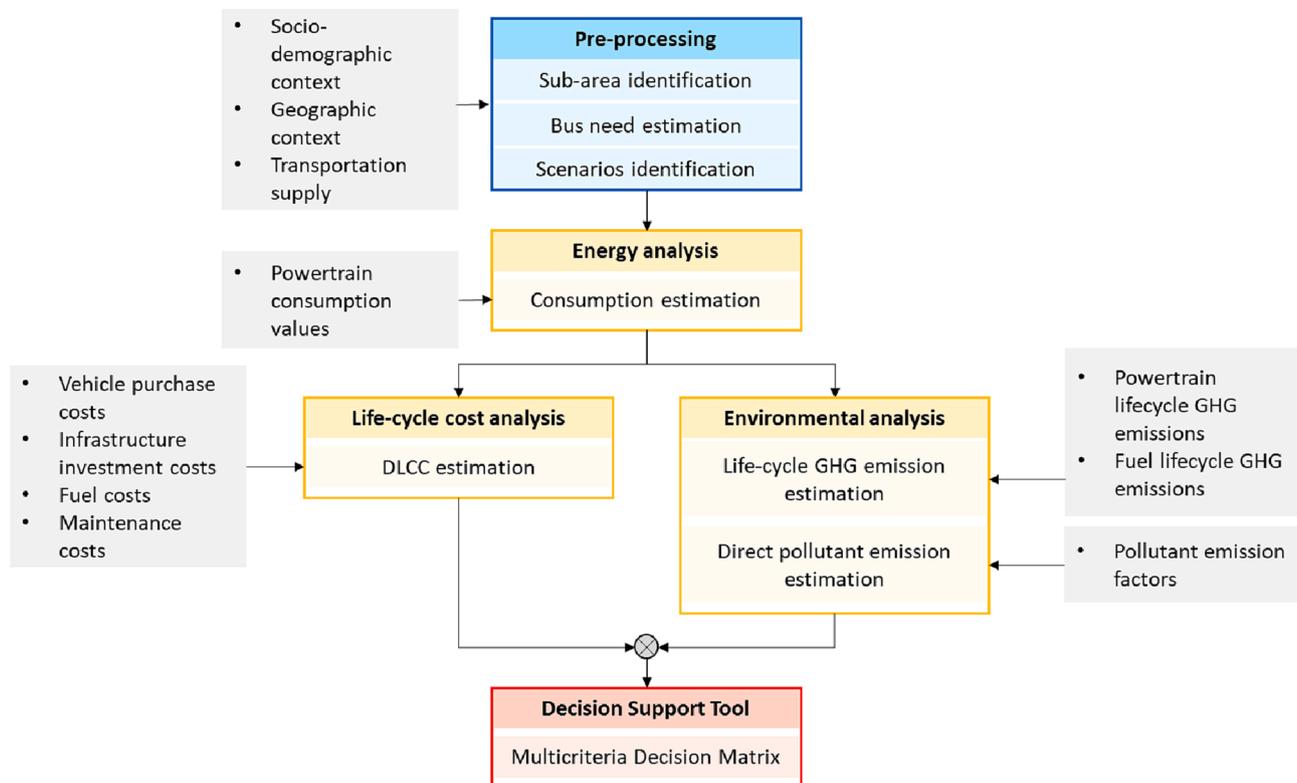


Fig. 2. Flowchart describing the proposed methodological approach.

be divided into homogeneous and heterogeneous models (Feng and Figliozzi, 2012): the formers aim to find the optimal replacement timing for an homogeneous fleet (for instance, buses that belong to the same type and/or age class have to be replaced together), while the second aim at providing the optimal mix for a multiple-type vehicle fleet (Hulagu and Celikoglu, 2022). Given the variety of vehicles of which a real bus fleet is made up of, heterogeneous models are more appropriate when solving real-world fleet replacement (Islam and Lownes, 2019). Moreover, technological detail should go hand in hand with service characterization since some powertrains might not be suitable for specific contexts of operations (urban vs. ex-urban). For example, long routes might impact the operations of electric buses with limited battery capacity and, in this regard, several studies do not consider this aspect (Sharma and Strezov, 2017; Castillo Munoz et al., 2019).

Nevertheless, these optimization tools, being focused on one-single objective (i.e. costs minimization), fall short to provide a comprehensive set of information to policy makers. The needed comprehensive approach can be identified among multicriteria ones. With reference to public transport means, life cycle costs can be complementing with environmental categories such as GHG emissions or local pollutants, as well as overall energy consumptions (Abbasi and Hadji, 2022; Abbasi et al., 2020; Safaei Mohamadabadi et al., 2009). All these information can be relevant for a holistic assessment of different fleet renewal scenarios (see for instance (Tong et al., 2017; Lajunen and Lipman, 2016)). Even though the methodological protocol can provide a consistent support to drive some general considerations, the application of these methodologies usually leads to case specific results. (Xu et al., 2015) showed the relevance of local geographical and operating condition when assessing the overall impact of current and incoming alternative fleets. The same applies for public transport service characteristics, such as frequency or capacity of the transit unit (Harris et al., 2020). Lastly, (McKenzie and Durango-Cohen, 2012) indicates how the purchase of clean-fuel buses, instead of traditional ones, come at both emission savings and an increase in investment costs (both for vehicles and charging infrastructures). In order to bypass the problem of the

trade-off between economic (i.e. life cycle costs) and environmental impacts (i.e. pollutants or greenhouse gases emissions), some studies propose optimization methods with both environmental and monetary constraints (Ercan et al., 2015; Emiliano et al., 2020): however the latter is based on only mere assumptions and should be customizable to meet individual LPT agency requirements, as suggested in (Islam and Lownes, 2019).

The aforementioned methods for fleet replacement are predominant in the literature and multicriteria ones seem to be the most suitable for a holistic viewpoint. However, the application of these methods to real case studies brings up some obstacles (Emiliano et al., 2020). They usually do not consider for external factors that may affect the bus consumption such as road slope and temperature, which, consequently, affect operating cost or local pollutant emission estimates (Carrese et al., 2013). Moreover, studies in the literature frequently imply assumptions regarding vehicles' usage during their useful life: they often use homogeneous mileage for vehicles, ignoring both real vehicle schedule and operational context.

This paper proposes a comprehensive methodology that considers real local geographical context (ambient temperature and road slope), service characteristics (urban and ex-urban line routes and frequencies) and bus fleet characteristics (size, year of registration, power train type, line allocation and km travelled) as input for both life-cycle economic and environmental analysis. Assessment criteria considered are the discounted over the analysis time horizon life-cycle cost, including investment (both for vehicle and infrastructure), operating, maintenance costs, and both global (GHG) and local (CO, NOx and PM2.5) emissions. The methodology aims at providing a multicriteria assessment matrix related to different a priori determined scenarios (characterized by both medium and long term transitions towards clean fuel buses), rather than at identifying an optimal scenario (as for instance in (James et al., 2021; Akti et al., 2020; Akti and Celikoglu, 2019; Hulagu and Celikoglu, 2019)): this would allow stakeholders having a decision support tool able to preliminary identify transition pathways to choose from.

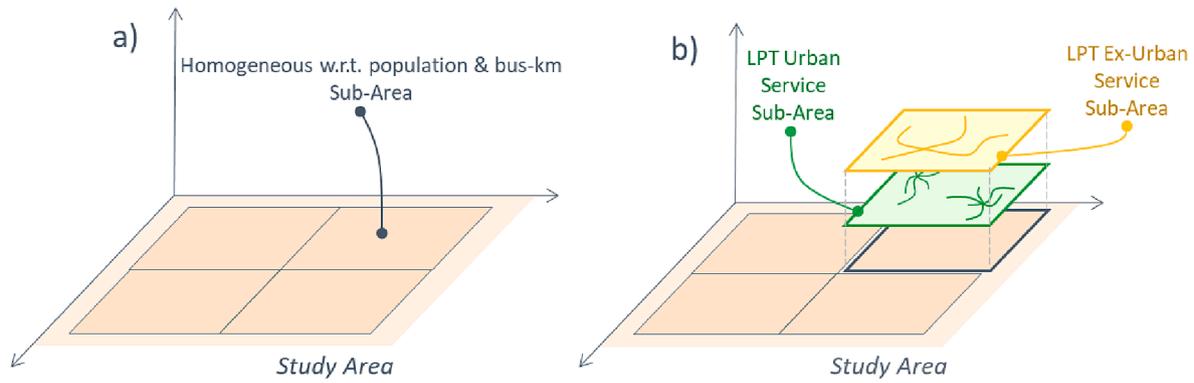


Fig. 3. Sub-Areas identification phase applying 'Horizontal' (a) and 'Vertical' (b) criteria: qualitative depiction.

### 3. Methodology

To assess the transition towards a clean-fuel bus fleet, this paper suggests the methodological approach schematically depicted in Fig. 2 and described in the following subsections.

#### 3.1. Pre-processing

##### 3.1.1. Input data

The first step consists in collecting data relating to the study area to be analysed. Information needed are related to:

- the socio-demographic context, i.e. the distribution of the resident population with a census-unit level of detail (extracted from (ISTAT, 2022) for the application in Section 4);
- the geographic context, i.e. ambient temperature and road slopes on which buses are in operation (extracted from (IlMeteo, 2022; Google, 2022) respectively for the application in Section 4);
- the transport supply, i.e. data relating to the bus fleet, public transport services and depot locations. Detailed data regarding the current bus fleet (i.e. the number of vehicles classified by size, year of registration, power train type and lines on which they are respectively in operation, km travelled by each single bus) are needed. Regarding the LPT service, line routes, frequencies and bus-km per year related to each line allow to set the current public transport service scenario, while the year-by-year LPT service related to the entire analysis time horizon can characterize the long-term perspective. For the application in Section 4, current transport supply data have been provided by the LPT Agency. For the long-term scenarios, data about the bus fleet (i.e. number and typology of buses per year) and the forecast km's travelled on each bus line in operation (as a product of the routes length and the lines frequencies) have been retrieved from the LPT planning documents (COLCVA LPT Agency, 2018).

##### 3.1.2. Sub-Areas identification

A zoning process is needed to identify sub-areas to be analysed. This can be done by applying both horizontal and vertical criteria. Horizontal criteria refer to homogeneity for both population and annual vehicle-km travelled by bus: the output is synoptically depicted in Fig. 3a. Vertical criteria refer instead to the LPT service type, with the aim of consider separately urban and ex-urban services (Fig. 3b).

##### 3.1.3. Bus needs estimation

Bus need estimation consists of both the evaluation of the number of buses needed to operate the LPT service in the analysis time span (i.e. considering also yearly total bus-km travelled variations and therefore bus fleet size changes) and the esteem of the number of new vehicles per year to be acquired to comply with both the planned service and the

disposal program. A constrained optimization is applied to generate a disposal programme, considering both the maximum vehicle lifetime and the maximum average fleet age as constraints. The output of this phase is the number of buses categorized by size that must be acquired in each year within the analysis time span for each sub-area as previously identified.

##### 3.1.4. Scenarios identification

To identify both vehicle and infrastructure technologies widely available on the market and those that will be available in the near future (i.e., those in which companies are currently investing in), a state of the art and/or focus groups involving relevant vehicle manufacturers and energy suppliers is suggested. These allow to properly set scenarios to be simulated, characterizing them according to suitable bus technologies for urban and ex-urban service, together with time horizons in which these technologies will be available, if not yet on the market.

#### 3.2. Energy analysis

Energy analysis is the backbone of both the environmental and the life-cycle cost assessment, being a step that feeds these two. It consists of the identification of the energy consumption of each powertrain and fuel. The energy requirements of CNG (Compressed Natural Gas) and LNG (Liquified Natural Gas) powered buses are expressed in reference to the diesel consumption value on an energy basis. In Eq. (1), the formula to compute the consumption of CNG and LNG buses is presented. The  $EC$  term represents the extra consumption on percentage basis,  $C_{bus}$  identifies the bus consumption, while  $LHV_{fuel}$  is the Lower Heating Value. The  $ref$  subscript refers to the bus and fuel reference that it is the diesel one in this application.

$$C_{bus} = \frac{C_{bus,ref} \cdot LHV_{fuel,ref} \cdot (1 + EC)}{LHV_{fuel}} \quad (1)$$

The extra consumption of CNG and LNG powertrains is 30% (C40 Cities Finance Facility, 2018). The consumption values of Battery Electric Buses (BEB), hydrogen Fuel Cell Electric Buses (FCEB) and Hybrid (e + H<sub>2</sub>), electric and hydrogen dual power, buses are reported in Table A1.2 in the Annex. The energy consumption values of the abovementioned powertrains are corrected according to both road slope and the outdoor temperature. The correction coefficients are reported in Fig. A1.1 and Fig. A1.2. The estimation of such corrective factors is performed using VCAM - Vehicle Consumption Assessment Model (Sanvito et al., 2020) tool which has been characterised for modelling buses' energy requirements: it is a lumped-parameter model able to reproduce powertrain longitudinal dynamics and additional consumption of auxiliary loads based on driving cycle inputs.

**Table 1**

Assumption on vehicle (12 m long bus) and infrastructure parametric costs. Within the proposed ranges in brackets, the lower bound refers to a 6 m long bus, while the upper bound to a 18 m long one.

Powertrain type	Vehicle purchase costs * [€*1000/bus]	Maintenance costs [€/km]	Power costs [€/km]	Infrastructure investment costs [€*1000/bus]
Diesel	210 (126–274)	0.35	0.41	0
CNG	230 (138–300)	0.37	0.23	21
LNG	260 (156–339)	0.39	0.30	12
BEB	440 (264–574)	0.21	0.20	35
Hybrid (e + H <sub>2</sub> )	555 (333–724)	0.24	0.48	35
FCEB	670 (402–874)	0.26	0.60	34

### 3.3. Life-cycle cost analysis

The economic analysis aims at estimating the total purchasing, operating, maintenance cost, including the residual value of the investment, for each alternative scenario previously identified. Table 1 shows the parametric costs, classified by powertrain type, assumed in the analysis. Particularly, bus purchase and maintenance costs have been initially estimated starting from (Conti et al., 2017; Berger, 2015; Berger, 2017; Kim et al., 2021; Barraza and Estrada, 2021; Johnson et al., 2020; Jefferies and Göhlich, 2020; Transportation Research Board, 2018; Topal and Nakir, 2018; Göhlich et al., 2018); power costs starting from (Berger, 2015; Berger, 2017; Zhang et al., 2014; Pamula and Pamula, 2020) and infrastructure investment costs starting from (Tong et al., 2017; Kim et al., 2021; Barraza and Estrada, 2021; Johnson et al., 2020; Göhlich et al., 2018; European Commission, 2020). Note that the latter refers only to charging infrastructure investment costs, where the costs of civil works are not considered. Preliminary estimates have been subsequently refined with data from Italian national sources relating to fuel prices, documents relating to Italian tender procedures and data provided by the panel of companies involved in the focus group, as mentioned in Par. 3.1.4. The types of vehicles that have been analysed are CNG and LNG powered, BEB, FCEB and Hybrid (e + H<sub>2</sub>) bus.

In case of BEBs, maintenance costs consider also a lump sum of 140'000€ for 330 kWh battery pack replacement after 450'000 km of operation: this value is estimated starting from currently common battery warranty parameters (Drive, 2020). Moreover, an overnight charging strategy has been assumed, identified as having the least impact from the bus operation programme viewpoint.

Given that a cash flow table is needed since these costs are distributed over the entire analysis time horizon, the Discounted Life-Cycle Cost (DLCC) is used to compare the different scenarios. Its formula is reported in Eq. (2).

$$DLCC = \sum_{t=1}^T \frac{C_t}{(1+r)^t} \quad (2)$$

where:

- $C_t$  is the total cost referred to the year  $t$  within the analysis time horizon (that goes from year 0 to  $T$ ), including also the residual value of the investment related to both vehicles and infrastructure at the end of the analysis time horizon;
- $r$  is the discount rate used to “discount” future costs to the base year of the analysis (this was assumed equal to 3% as suggested by the Italian Guidelines to CBA, (MIT, 2017).

### 3.4. Environmental analysis

This study considers the following bus emission categories: life-cycle greenhouse gas emissions (Par. 3.4.1) and direct local polluting emissions (Par. 3.4.2).

#### 3.4.1. Life-cycle greenhouse emissions

Life-cycle emissions are computed considering the following stages:

- material extraction;
- manufacturing (bodywork);
- maintenance;
- battery manufacturing;
- well-to-tank (WTW);
- tank-to-wheel (TTW);
- end-of-life (including recycling).

The emission contribution is displayed in gCO<sub>2</sub>-equivalent/(vehicle • km).

**3.4.1.1. Material extraction, manufacturing (bodywork) and maintenance.** For what concerns material extraction, manufacturing and maintenance stages, the computation of the specific greenhouse gas emissions is based on the emission factors found in (Nordelöf et al., 2019). The emission coefficients are expressed in gCO<sub>2</sub>-eq/(km • person) so, in Eq. (3), they are converted such that they refers to the vehicle as a functional unit.

$$e_{i,vkm} = e_{i,pkm} \bullet \overline{n_{pass,v}} \quad (3)$$

In Eq. (3),  $e_{i,vkm}$  refers to the specific value of greenhouse gas emissions measured in gCO<sub>2</sub>-eq/(vehicle • km), while  $e_{i,pkm}$  are the same emissions expressed in gCO<sub>2</sub>-eq/(passenger • km). Those values are tabulated and retrieved from (Nordelöf et al., 2019). The parameter  $\overline{n_{pass,v}}$  stands for the average occupancy rate per vehicle.

**3.4.1.2. Battery manufacturing.** Battery production wise, the contribution of life-cycle emissions is computed for all the powertrains that host an onboard traction battery, namely BEBs, FCEBs and Hybrid (e + H<sub>2</sub>) buses. The emission factor of the battery production is dependent on the energy requirements that can be split in electricity and heat sources. (Aichberger and Jungmeier, 2020) identifies the energy needs for battery production as 100 kWh<sub>el</sub>/kWh<sub>bc</sub> for electricity ( $cons_{el}$ ) and 50 kWh<sub>th</sub>/kWh<sub>bc</sub> for thermal requirements ( $cons_{th}$ ), where  $bc$  subscript stands for the functional unit *battery capacity*. On the one hand, the emission factor related to the electricity mix is selected considering 677 gCO<sub>2</sub>-eq/kWh (IEA, 2022) that corresponds to China power generation carbon intensity, since it is one of the world major battery manufacturer. The emission factor related to the heat production ( $ef_{th}$ ) from natural gas is selected starting from (EPA - United States Environmental Protection Agency, 2020) and is complemented with tabulated global warming potentials (Greenhouse Gas Protocol, 2014). The resulting emission factor is 367 gCO<sub>2</sub>-eq/kWh. In Table A1.1, battery sizes (*battcap*) of each technology are displayed.

**3.4.1.3. Well-to-Tank and Tank-to-Wheel.** In case of internal combustion engine technologies relying on liquid or gaseous fuels such as diesel, CNG and LNG, well-to-tank emissions are computed as shown in Eq. (4):

$$e_{WTT,i} = LHV_i \bullet fuelconsumption_i \bullet ef_{WTT,i} \quad (4)$$

$$\forall i \in \{diesel, CNG, LNG\}$$

where  $ef_{WTT,i}$  is the emission factor expressed in gCO<sub>2</sub>-eq/MJ corresponding to the well-to-tank stage. These values are retrieved from (Edwards et al., 2004). The reference fuel consumption for each

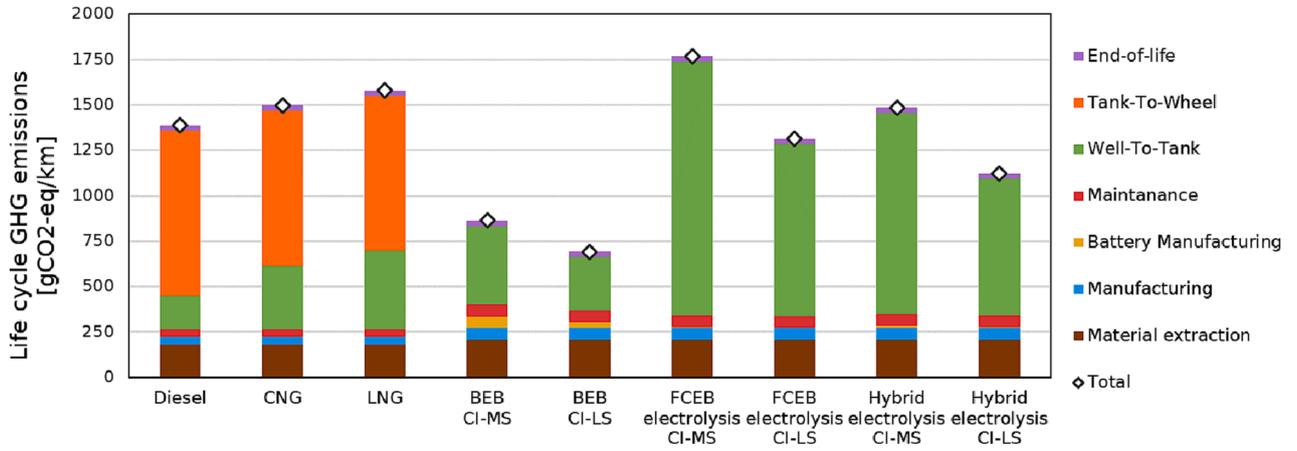


Fig. 4. Emission factors expressed in  $\text{gCO}_2\text{eq/km}$  for each considered bus powertrain, highlighting different life-cycle stages.

Table 2

Electricity grid carbon intensities used for WTT and battery manufacturing life-cycle stages for medium-term (2020–2025) and long-term (2026–2033) scenarios.

Parameter	Unit of measurement	Medium-term scenario	Long-term scenario
Electricity grid carbon intensity for WTT stages	$\text{gCO}_2\text{-eq/kWh}$	349	236
Electricity grid carbon intensity for battery manufacturing	$\text{gCO}_2\text{-eq/kWh}$	677	367

considered technology is reported in the Annex (Table A1.2) as well as the reference lower heating values (Table A1.3).

In case of battery electric powertrains, a country-averaged electricity emission factor ( $ef_{grid}$ ) is assumed, with a 97% charging efficiency ( $\eta_{charging}$ ) (Yusof et al., 2021).

$$e_{WTT,i} = \frac{electricityconsumption_i \cdot ef_{grid}}{\eta_{charging}} \quad (5)$$

$$\forall i \in \{BEB\}$$

In case of FCEB buses, only hydrogen production through electrolysis is assumed: the Steam Methane Reforming (SMR) process is excluded due to its environmental concern and the use of Carbon Capture and Storage (CCS) remains a non-industrial ready technology. The well-to-tank contribution is then computed as reported in Eq. (6): variables refer to the electrolyser efficiency ( $\eta_{electrolyzer}$ ) and to the emission factor related to the reference energy mix ( $ef_{grid}$ ). Electrolyser efficiency is assumed equal to  $50 \text{ kWh}_{el}/\text{kgH}_2$  (C40 Cities Finance Facility, 2018) and the grid emission factor corresponds to the Italian one, as previously mentioned.

$$e_{WTT,i} = fuelconsumption_i \cdot \eta_{electrolyzer} \cdot ef_{grid} \quad (6)$$

$$\forall i \in \{FCEB + electrolyzer\}$$

For the hybrid configuration ( $e + \text{H}_2$ ), the WTT emissions are computed as the weighted average between the single contributions of BEB and FCEB: this has been computed through Eq. (7), including the so-called hybridization factor ( $HF$ ) that fixes the ratio of kilometres travelled using the fuel cell over the total. The hybridization factor is conservatively assumed equal to 0.7, whose estimation derives from the analysis of the Braunschweig bus driving cycle (National Renewable Energy Laboratory, 2022). In fact, its average driving speed is selected to differ from low-speed and high-speed regimes. It turns out that the distance covered in high-speed regimes falls between 70% and 80% of the total

driving cycle distance. High-speed regime is associated with ex-urban operations and therefore with fuel-cell utilization.

$$e_{WTT,i} = e_{WTT,FCEB} \cdot HF + e_{WTT,BEB} \cdot (1 - HF) \quad (7)$$

$$\forall i \in \{hybridhydrogenandelectric\}$$

Regarding Tank-to-Wheel (TTW) emissions, these are null in case of electric powertrains (BEB, FCEB and Hybrid  $e + \text{H}_2$ ) since no combustion processes occur onboard, while for the other technologies considered in the study, the TTW emissions are calculated as shown in Eq. (8).

$$e_{TTW,i} = LHV_i \cdot fuelconsumption_i \cdot ef_{TTW,i} \quad (8)$$

$$\forall i \in \{diesel, CNG, LNG\}$$

The parameter  $ef_{TTW,i}$  is the emission factor expressed in  $\text{gCO}_2\text{-eq/MJ}$  corresponding to tank-to-wheel consumption and it is retrieved from (Edwards et al., 2004). It is worth noting that the tank-to-wheel emission factor for CNG and LNG are computed as summation of the combustion term and the fugitive methane emissions which values are reported in Table A1.4.

**3.4.1.4. End-of-life.** The end-of-life emission factors are elaborated from (Nordelöf et al., 2019) and then complemented with emission reduction factors related to battery recycling. The proposed framework considers also recycling emission savings elaborated on (Aichberger and Jungmeier, 2020) that estimates the net average value of  $-21 \text{ kgCO}_2\text{-eq/kWh}_{bc}$ . The current study does not include any battery recycling effect since the processes have not yet reached a technological maturity.

In Fig. 4, the life-cycle greenhouse emission values for buses are displayed and categorised according to the different life-cycle stages (detailed numerical values are reported in Table A1.5). It is worth mentioning that the average electricity production carbon intensity is  $349 \text{ gCO}_2\text{eq/kWh}$  (IEA, 2021) in the Medium-term Scenario (MS) and  $236 \text{ gCO}_2\text{eq/kWh}$  in the Long-term Scenario (LS) corresponding to the Italian case study.

Battery life-cycle footprint results to be  $86 \text{ kgCO}_2\text{-eq/kWh}_{bc}$  based on the stated assumptions (this is consistent with current studies that identifies a wide plausible range between 39 and  $196 \text{ kgCO}_2\text{-eq/kWh}_{bc}$  according to (Melin, 2019).

The study considers two different time spans: a medium-term scenario (MS), 2020–2025, and a long-term scenario (LS), 2026–2033. Emission factors are varied according to the time horizon as reported in Table 2.

Medium-term scenario electricity grid intensity for WTT stages is set equal to the national value of Italy elaborated starting from (IEA, 2021). The value selected for battery production equals the electricity carbon emission of China. The long-term value of electricity grid carbon

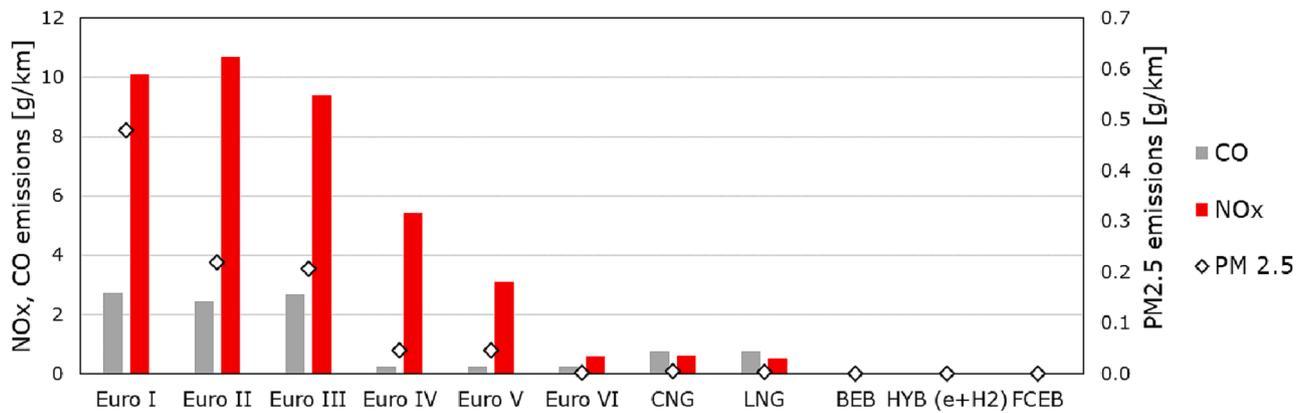


Fig. 5. NOx, CO and PM2.5 emission factors expressed in g/km (EEA, 2020).



Fig. 6. Location of the Como-Lecco-Varese basin. Source for terrain background layer: Open Street Map.

intensity for WTT stages is elaborated starting from the pledges submitted by Italy consisting in the achievement of 55% of renewable electricity penetration by 2030 as reported (IEA, 2021), while the Chinese grid carbon intensity is reduced to the equivalent emission factor of natural gas (EPA - United States Environmental Protection Agency, 2020).

### 3.4.2. Direct local polluting emissions

Direct local pollution is evaluated by tracking powertrain emissions of finer particulate matter (PM2.5), CO and NO<sub>x</sub>. The values are elaborated starting from data in (EMEP, 2022; EEA, 2020). The resulting

parameters are shown in Fig. 5 and reported in detail in Table A1.6.

### 3.5. Multicriteria decision matrix

With the aim of comparing different scenarios identifying the non-dominated ones (i.e. scenarios for which there is not any other scenario that improves the satisfaction level of at least one assessment criteria without making anyone worse), a multicriteria decision matrix is finally proposed. It has a number of column equal to the number of scenarios analysed and 5 rows, one for each evaluation criteria: discounted life-cycle cost and GHG, CO, NO<sub>x</sub> and PM2.5 emissions.

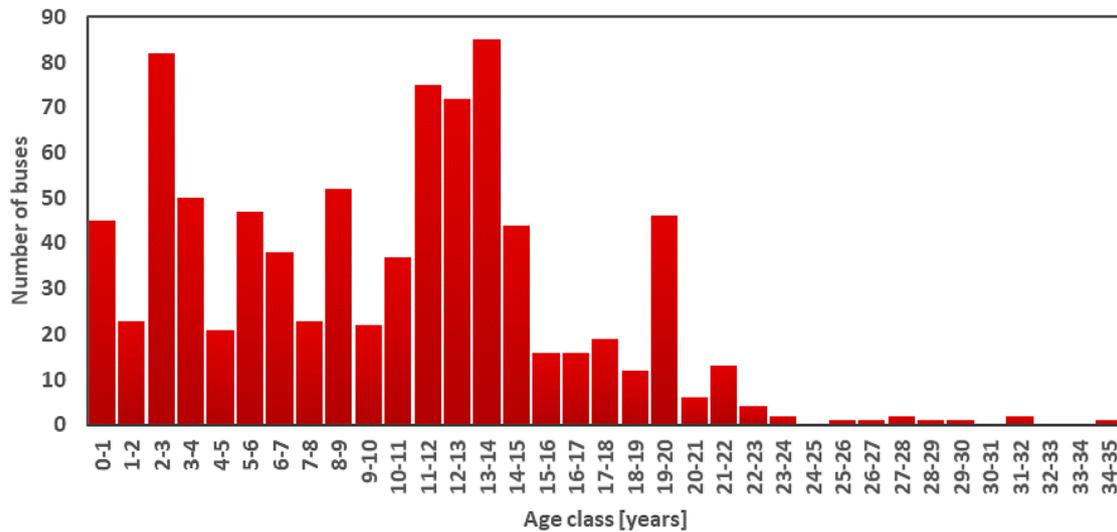


Fig. 7. Current bus fleet distribution by age class.

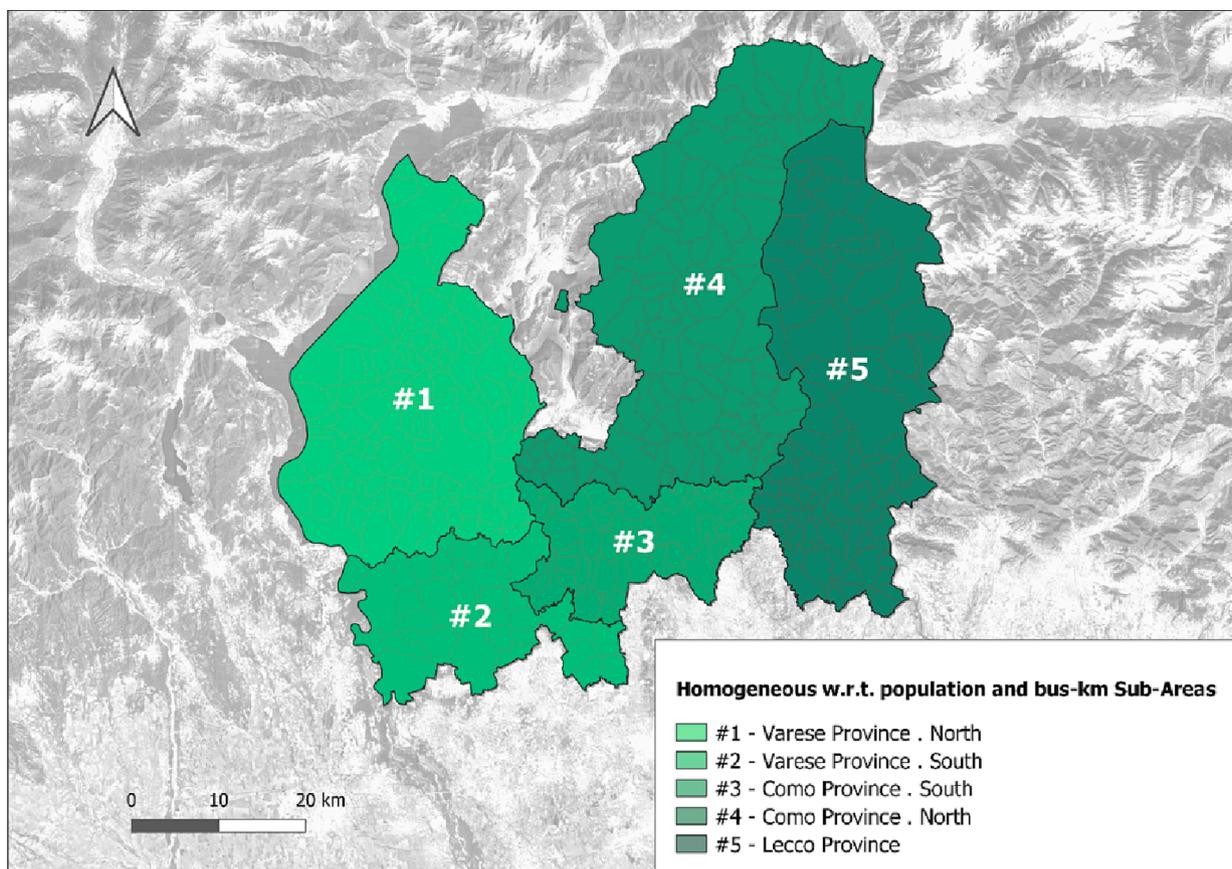


Fig. 8. Homogeneous w.r.t. population and bus-km sub-areas. Source for terrain background layer: Open Street Map.

#### 4. Case study: The Como-Lecco-Varese basin

The methodology has been applied to the Italian basin composed of the provinces of Como, Lecco and Varese in the Lombardy Region (Fig. 6). Step-by-step results are reported in the following subsections, except for energy analysis results that have been reported in Table A1.2, Table A1.3, Fig. A1.1, Fig. A1.2 in the Annex.

##### 4.1. Pre-processing

###### 4.1.1. Input data

Como-Lecco-Varese current bus LPT service is carried out by 17 companies which operate a total of about 28.8 million buses-km per year divided between 192 lines. Future LPT service (as described in (COLCVA LPT Agency, 2018)) provides for both a rationalization of the number of bus lines (180 lines, -6.3% with respect to the current scenario), and an increase of 7.5% in the number of bus-km per year (about 31 million

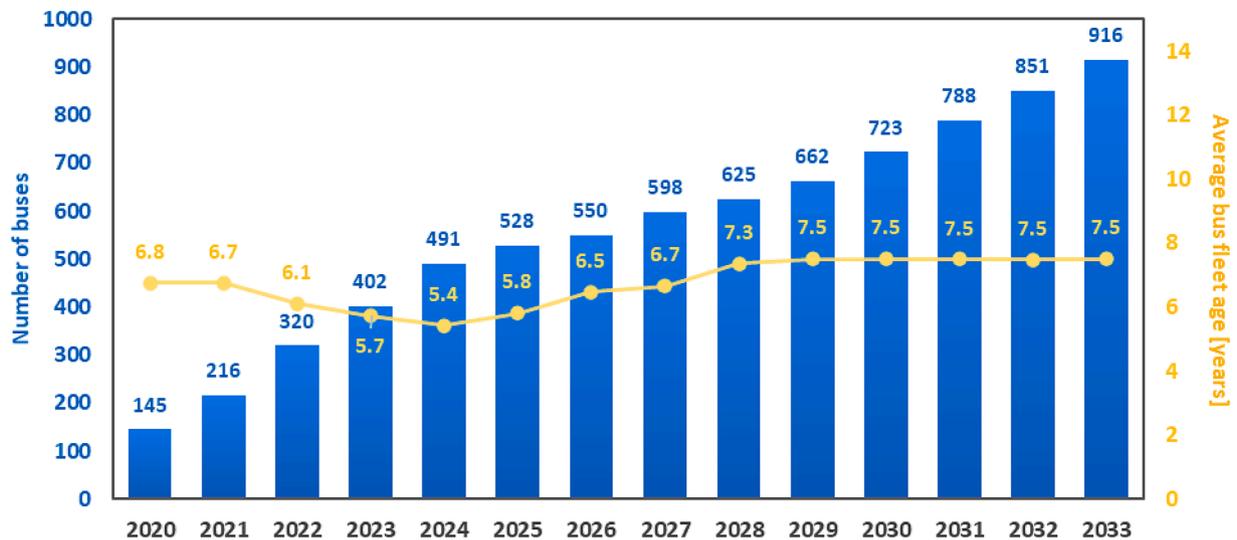


Fig. 9. Bus need estimation and average fleet age over the whole analysis time horizon.

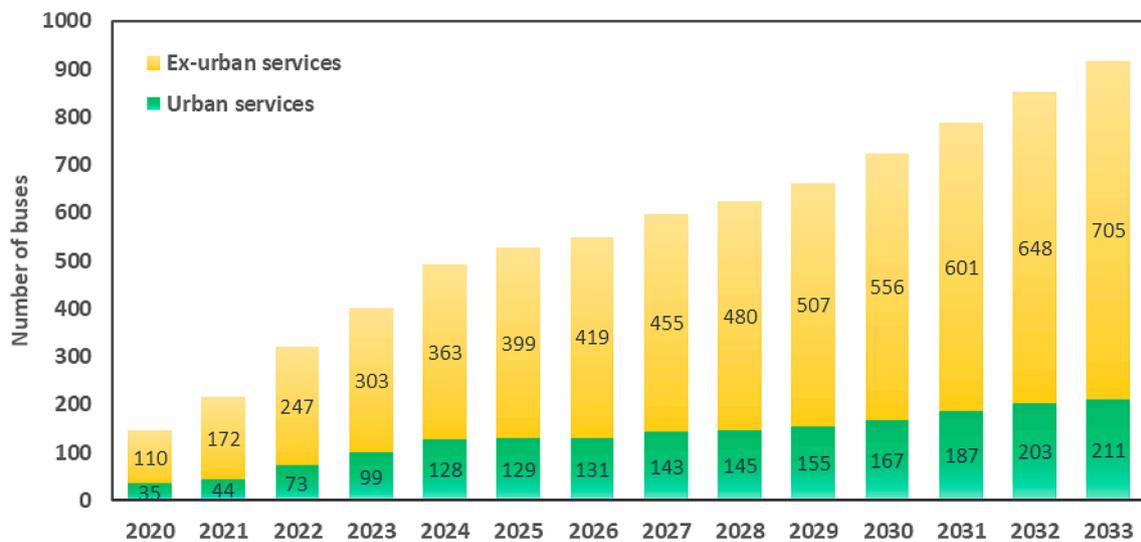


Fig. 10. Bus need estimation, classified by LPT service type, over the whole analysis period.

bus-km). The current bus fleet consists of 859 vehicles, of which 59 are less than 8 m long, 90 between 8 and 10 m, 646 between 10 and 12 m, 64 longer than 12 m (of which 52 are articulated). About 99% of the vehicle fleet has diesel engine (of which 22% are of environmental class equal or lower than Euro III, 46% are Euro IV or V, 32% are Euro VI), while the percentages of gas powered or electric-hybrid vehicles are negligible. The distribution of the current bus fleet by age (Fig. 7) shows that 145 buses are currently over 15 years old (approximately 17% of the entire fleet, which has an average age of about 10 years).

4.1.2. Sub-Areas identification

Based on the considerations in Par. 3.1.2, ten sub-areas have been identified: five homogeneous w.r.t. population and yearly bus-km portions of the territory have been selected (Fig. 8) and for each of them urban and ex-urban LPT services have been separately considered. LPT services have been distinguished in urban and ex-urban by considering the spatial context they serve (for instance, services inside the same city have been classified as urban, while those connecting different cities as ex-urban), resulting in an average (one-way) service mileage of about 5 km for urban services and 18 km for ex-urban ones.

For sake of simplicity and overall readability, results for the entire

study area will be reported in the continue of this paper: these must be intended as the summation of all the outcomes of the sub-areas analysed.

4.1.3. Bus needs estimation results

The number of buses per year to be acquired (i.e. bus need) consists of two aliquots: the first concerns to buses to be acquired due to vehicles' disposals, while the second refers to buses to be purchased due to an increased fleet size (current 859 buses vs. future 916 buses) needed to operate the increased in bus-km planned service in the long term.

The first aliquot matches a bus disposal programme and is therefore estimated through a constrained optimization starting from current fleet data. As for the Basin Program (COLCVA LPT Agency, 2018), two simultaneous constraints have been introduced: these are 7.5 years as the maximum average fleet age and 15 years age maximum for a single vehicle replacement. The second aliquot is instead estimated year by year by the difference between number of buses needed to operate the service and those that compose the fleet in the base year of the analysis. Fig. 9 shows both the annual requirement (i.e. the cumulated number of buses to be purchased) and the evolution of average bus fleet age, considering both acquisitions and disposals.

With reference to the annual requirement, the number of buses to be

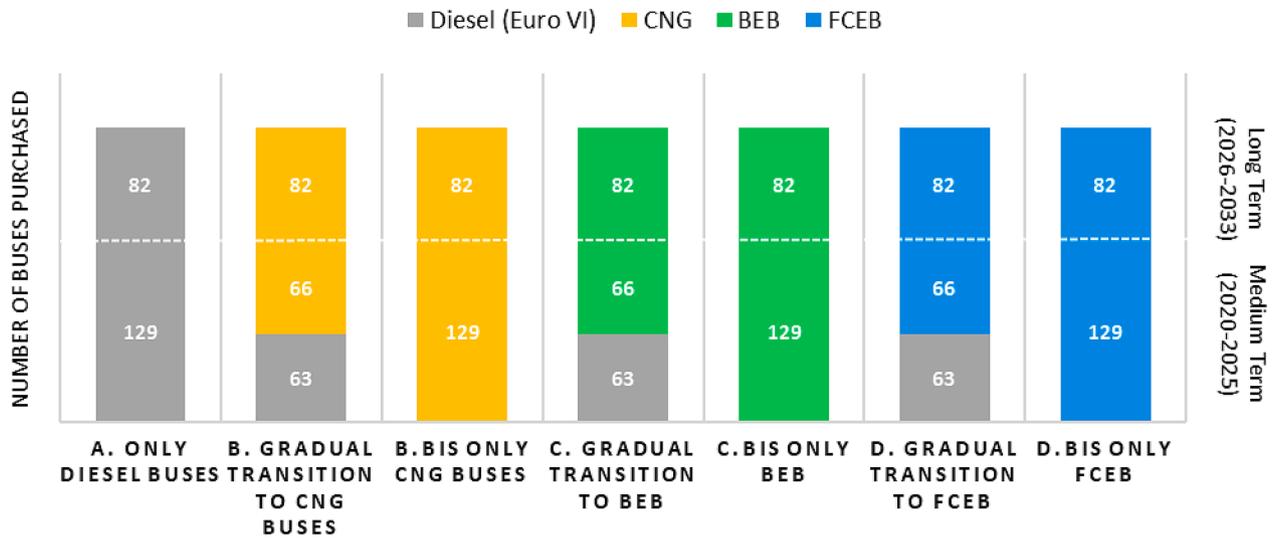


Fig. 11. Urban LPT service scenarios.

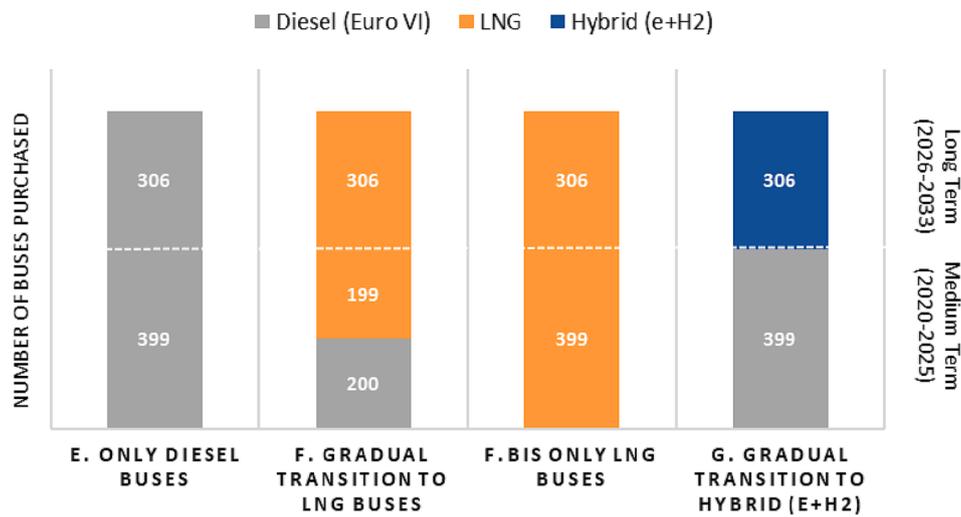


Fig. 12. Ex-urban LPT service scenarios.

Table 3

Discounted life-cycle cost (DLCC) related to the entire analysis time horizon for both urban and ex-urban LPT service scenarios and breakdown for cost items. Values are all expressed in million euros.

Urban LPT service scenarios	DLCC	Discounted Vehicle costs	Discounted Infrastructure costs	Discounted Maintenance costs	Discounted Power costs	Discounted Residual value
A. Only Diesel buses	75.8	38.3	0.0	23.7	27.7	-13.9
B. Gradual transition to CNG buses	81.1	42.6	2.1	24.9	26.5	-15.1
B.bis Only CNG buses	83.4	44.6	3.4	25.7	25.7	-16.1
C. Gradual transition to BEB	90.3	66.5	4.4	24.8	19.8	-25.2
C.bis Only BEB	99.0	80.2	6.5	27.1	14.2	-29.0
D. Gradual transition to FCEB	118.3	94.8	4.3	20.1	36.5	-37.4
D.bis Only FCEB	146.4	122.1	6.3	17.6	42.7	-42.3
Ex-urban LPT service scenarios	DLCC	Discounted Vehicle costs	Discounted Infrastructure costs	Discounted Maintenance costs	Discounted Power costs	Discounted Residual value
E. Only Diesel buses	202.9	126.8	0.0	52.9	66.0	-42.8
F. Gradual transition to LNG buses	210.4	147.5	5.1	56.5	55.9	-54.5
F.bis Only LNG buses	215.2	157.0	7.4	59.0	48.8	-56.9
G. Gradual transition to Hybrid (e + H2)	236.3	205.2	8.1	49.9	73.9	-100.8

**Table 4**

Total LCA GHG emission factors and relative changes with respect to diesel powertrain in both a medium-term and a long-term scenario.

	Energy carrier production	uom	Diesel	CNG	LNG	BEB	FCEB Electrolysis	Hybrid (e + H <sub>2</sub> ) Electrolysis
Medium-termScenario	Total LCA emission factor	[gCO <sub>2</sub> eq/km]	1389	1499	1579	864	1769	1485
	Emission change wrt Diesel	[-]	-	+8%	+14%	-38%	+27%	+7%
Long-term Scenario	Total LCA emission factor	[gCO <sub>2</sub> eq/km]	1389	1499	1579	692	1314	1121
	Emission change wrt Diesel	[-]	-	+8%	+14%	-50%	-5%	-19%

**Table 5**

Results of the environmental analysis conducted for both urban and ex-urban LPT service scenarios. \* Percentage variation with reference to an Only Diesel buses (urban or ex-urban) scenario.

Urban LPT service scenarios	Medium term (2020–2025)				Long term (2026–2033)				Total			
	GHG - CO <sub>2</sub> -eq	PM 2.5	CO	NOx	GHG - CO <sub>2</sub> -eq	PM 2.5	CO	NOx	GHG - CO <sub>2</sub> -eq	PM 2.5	CO	NOx
A. Only Diesel buses	23 kton	0.03 ton	4 ton	10 ton	60 kton	0.09 ton	10 ton	26 ton	84 kton	0.12 ton	14 ton	36 ton
B. Gradual transition to CNG buses *	4%	67%	125%	120%	5%	56%	150%	142%	4%	58%	136%	133%
B.bis Only CNG buses *	9%	133%	225%	230%	8%	89%	240%	227%	7%	100%	236%	225%
C. Gradual transition to BEB *	-17%	-33%	-50%	-50%	-32%	-67%	-60%	-62%	-29%	-58%	-64%	-58%
C.bis Only BEB *	-39%	-100%	-100%	-100%	-50%	-100%	-100%	-100%	-48%	-100%	-100%	-100%
D. Gradual transition to FCEB *	13%	-33%	-50%	-50%	-3%	-67%	-60%	-62%	1%	-58%	-64%	-58%
D.bis Only FCEB *	30%	-100%	-100%	-100%	-5%	-100%	-100%	-100%	4%	-100%	-100%	-100%
Ex-urban LPT service scenarios	Medium term (2020–2025)				Long term (2026–2033)				Total			
	GHG - CO <sub>2</sub> -eq	PM2.5	CO	NOx	GHG - CO <sub>2</sub> -eq	PM2.5	CO	NOx	GHG - CO <sub>2</sub> -eq	PM2.5	CO	NOx
E. Only Diesel buses	72 kton	0.1 ton	12 ton	31 ton	193 kton	0.28 ton	31 ton	84 ton	265 kton	0.38 ton	43 ton	115 ton
F. Gradual transition to LNG buses *	7%	60%	117%	110%	9%	61%	158%	136%	8%	61%	147%	129%
F.bis Only LNG buses *	14%	110%	233%	219%	13%	100%	248%	215%	14%	100%	247%	216%
G. Gradual transition to Hybrid (e + H <sub>2</sub> ) *	0%	0%	0%	0%	-5%	-29%	-26%	-27%	-4%	-18%	-19%	-20%

**Table 6**

Multicriteria decision matrix for the urban context.

Urban LPT service	A. Only Diesel buses	B. Gradual transition to CNG buses	B.bis Only CNG buses	C. Gradual transition to BEB	C.bis Only BEB	D. Gradual transition to FCEB	D.bis Only FCEB
DLCC [mln€]	75.8	81.1	83.4	90.3	99.0	118.3	146.4
GHG - CO <sub>2</sub> -eq [kton]	84	87	90	60	44	85	87
PM 2.5 [ton]	0.12	0.19	0.24	0.05	0.00	0.05	0.00
CO [ton]	14	33	47	5	0	5	0
NOx [ton]	36	84	117	15	0	15	0

**Table 7**

Multicriteria decision matrix for the ex-urban context.

Ex-urban LPT service	E. Only Diesel buses	F. Gradual transition to LNG buses	F.bis Only LNG buses	G. Gradual transition to Hybrid (e + H <sub>2</sub> )
DLCC [mln€]	202.9	210.4	215.2	236.3
GHG - CO <sub>2</sub> -eq [kton]	265	286	301	255
PM 2.5 [ton]	0.38	0.61	0.76	0.31
CO [ton]	43	106	149	35
NOx [ton]	115	263	363	92

**Table A1.1**

Traction battery sizes for BEB, Hybrid bus (e + H<sub>2</sub>) and FCEB.

Technology	Unit of measurement	Value
BEB	kWh	330
Hybrid bus (e + H <sub>2</sub> )	kWh	60
FCEB	kWh	50

purchased in the medium-term, i.e. up to 2025, is equal to 528 vehicles; while this is equal to 916 vehicles in the long-term (year 2033). With reference to the evolution of the average age of the vehicle fleet, the constraint of 15 years as the maximum age of a bus is the dominant one until the year 2029, when the other constraint becomes the most stringent, thus stabilizing the average age of the fleet at a value close to the limit of 7.5 years. Fig. 10 shows the breakdown of annual bus

**Table A1.2**  
Vehicle consumption reference values.

Powertrain	Unit of measurement	Value	References
Diesel Bus	L/100 km	36.0	(C40 Cities Finance Facility, 2018; Berger, 2017; Paul and Yamada, 2014; Vepsäläinen et al., 2018)
BEB	kWh/km	1.8	
FCEB	kg/100 km	8.0	(C40 Cities Finance Facility, 2018; Berger, 2017)
LNG Bus	kg/100 km	34.7	
CNG Bus	kg/100 km	35.5	
LNG and CNG additional consumption with respect to diesel bus on energy basis	-	0.3	
Hybridization factor of Hybrid hydrogen-electric	kmH2/kmtot	0.7	

**Table A1.3**  
Fuel specifications.

Fuel	Unit of measurement	LHV	Unit of measurement	Density
Diesel	MJ/L	36.0	kg/L	36.0
Hydrogen	MJ/kg	8.0	kg/L	120.0
LNG	MJ/kg	48.6	kg/L	0.435
CNG	MJ/kg	47.5	kg/L	0.175

requirements by service type. Ex-urban buses correspond to the highest annual percentage share of vehicles to be purchased: this share is approximately equal to 75% by 2025, while it rises to 77% in 2033.

4.1.4. Scenarios identification results

Scenarios identification envisaged discussions with the most relevant vehicle manufacturers and energy suppliers operating in Italy. A total of 5 focus groups have been organized between September 2020 and April 2021, involving company representatives dealing with tasks related to industrial strategic planning and research and development. Different views about urban and ex-urban LPT service emerged. With reference to the first, the introduction of electric buses (BEB or FCEB) is foreseen in both the medium and the long term. At the same time, the fact that some Italian cities have already planned investments in CNG buses replacing

traditional diesel vehicles has been noted. The ex-urban service instead differs from the urban one mainly due to the delayed in time wide market availability of long-range BEBs. This is the reason why company representatives involved in focus groups expect the simultaneous availability of diesel (Euro VI) and LNG powered vehicles in both medium and long term, while Hybrid (e + H<sub>2</sub>) electric and hydrogen dual power buses are foreseen in the long run. The above considerations have been reported in Fig. 11 and Fig. 12, summarizing scenarios for the urban and ex-urban service respectively. Scenarios A and E (i.e., those providing only for investments in new diesel buses) have been included to simulate conservative with respect to the current situation investment plans. Moreover, scenarios whose codes start with the same letter and differ for the suffix “Bis” are characterized by investments in the same bus technology, but in a more or less gradual way.

4.2. Life-cycle costs analysis results

Identified scenarios have been simulated from an economic perspective. Discounted life-cycle costs for both urban and ex-urban LPT service scenarios are shown in Table 3, where the breakdown for all the (discounted) cost items considered in the analysis is also reported.

Scenarios that provide for the introduction of alternative to diesel powertrains are more expensive from a life-cycle perspective: for the urban case, the “D.bis Only FCEB” scenario increases the discounted life cycle cost by +93% compared to the “A. Only Diesel buses” scenario; for the ex-urban one, a gradual transition to Hybrid (e + H<sub>2</sub>) buses, i.e. Scenario G., would increase life cycle costs by +16% compared to a conservative scenario with only investments in new diesel buses (Scenario E.). It is also worth noting how, by investing in alternative to diesel technologies, the discounted life cycle power costs decrease, up to 56% in case only new urban BEB acquired (Scenario C.bis). This consideration is not true for fully or partially hydrogen powered buses (i.e., FCEB or Hybrid e + H<sub>2</sub>) due to the current high cost of this energy carrier.

4.3. Environmental analysis results

The total LCA GHG emission factors for each technology are reported in Table 4 providing the percentage variation of specific emissions with respect to both the reference diesel powertrain and time span.

Considering the medium-term (2020–2025), it stands out that BEB is the only powertrain able to contribute to the emissions reduction with respect to the diesel bus. The FCEB and the hybrid powertrain emission factors are strongly dependent by the time horizon considered (medium vs. long term). In the long-term scenario, these powertrains become

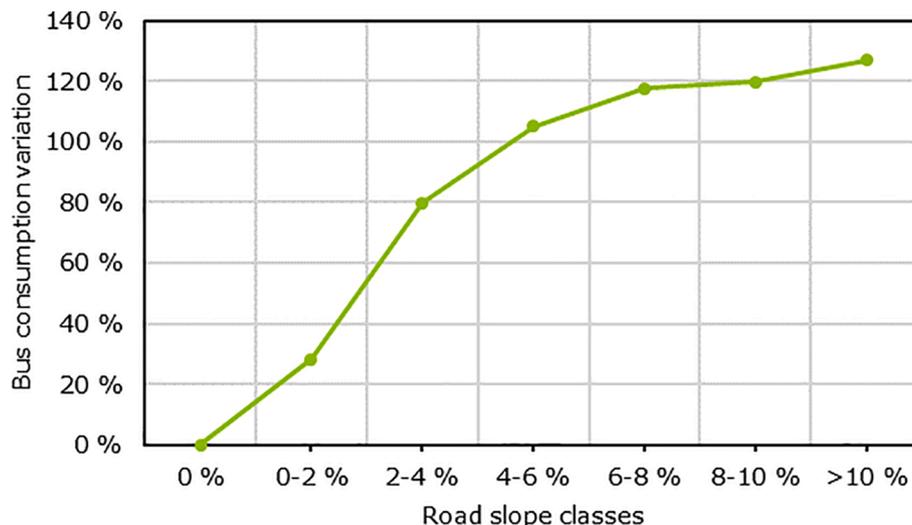


Fig. A1.1. Bus consumption variation due to road slope computed by VCAM (Sanvito et al., 2020).

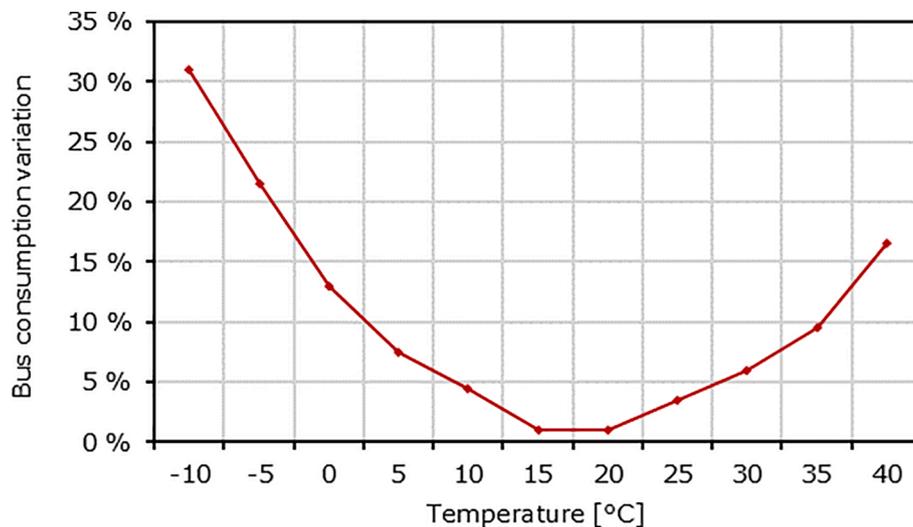


Fig. A1.2. Bus consumption variation due to outdoor temperature computed by VCAM (Sanvito et al., 2020).

Table A1.4  
LCA emission factor for different fuels.

Parameter	Unit of measurement	LCA emission factor (Edwards et al., 2004)
Hydrogen from Natural Gas (SMR)	gCO2-eq/MJH2	118.0
Hydrogen from Coal	gCO2-eq/MJH2	240.0
Conventional Diesel - WTT	gCO2-eq/MJ	15.4
Conventional Diesel - TTW	gCO2-eq/MJ	73.3
LNG - WTT	gCO2-eq/MJ	19.3
LNG - WTT (CH4 leakage)	gCO2-eq/MJ	11.8
LNG - TTW	gCO2-eq/MJ	56.3
CNG - WTT	gCO2-eq/MJ	13.1
CNG - WTT (CH4 leakage)	gCO2-eq/MJ	12.1
CNG - TTW	gCO2-eq/MJ	56.3
CH4 Leakage as share of the vehicle consumption	%	2.3

more environmentally sustainable if compared to traditional diesel buses. Both BEBs and FCEBs based on green hydrogen supply, show a high share of emissions attributable to Well-to-Tank emissions, respectively 50% and 79% of the total, because of the major influence of electricity mix emission factor. In the long-term scenarios, along with a reduction of the electricity grid emission factor, the same values reduce to 42% and 72% respectively for the BEB and the FCEB. Conversely, CNG and LNG have a greater life-cycle carbon impact compared to diesel, +8% and +14% respectively.

Both urban and ex-urban LPT service scenarios have been simulated from the environmental viewpoint and results are shown in Table 5.

In the urban case, the most performing scenario from an environmental perspective is the one based on 100% BEB acquisition. The conversion of the urban bus fleet into a full battery electric one gives rise to a GHG emission saving of 40 kton of CO<sub>2</sub>-eq with respect to Scenario A (-48%). In the ex-urban case, among the simulated scenarios, a gradual transition to Hybrid (e + H<sub>2</sub>) buses is the one that maximizes both global

Table A1.5  
Emission factors expressed in gCO<sub>2</sub>eq/km for each considered bus powertrain, highlighting different life-cycle stages.

Energy carrier production	uom	Diesel	CNG	LNG	BEB CI-MS	BEB CI-LS	FCEB Electrolysis CI-MS	FCEB Electrolysis CI-LS	Hybrid (e + H <sub>2</sub> ) Electrolysis CI-MS	Hybrid (e + H <sub>2</sub> ) Electrolysis CI-LS
Material extraction	[gCO <sub>2</sub> eq/km]	184	184	184	210	210	210	210	210	210
Manufacturing	[gCO <sub>2</sub> eq/km]	39	39	39	62	62	62	62	62	62
Battery Manufacturing	[gCO <sub>2</sub> eq/km]	-	-	-	65	34	6	3	12	6
Maintenance	[gCO <sub>2</sub> eq/km]	43	43	43	66	66	66	66	66	66
Well-To-Tank	[gCO <sub>2</sub> eq/km]	185	348	430	432	292	1396	944	1107	748
Tank-To-Wheel	[gCO <sub>2</sub> eq/km]	912	857	855	0	0	0	0	0	0
End-of-life	[gCO <sub>2</sub> eq/km]	26	29	29	29	29	29	29	29	29
Battery recycling	[gCO <sub>2</sub> eq/km]	-	-	-	-	-	-	-	0	0
Total LCA emission factor	[gCO <sub>2</sub> eq/km]	1389	1499	1579	864	692	1769	1314	1485	1121
Emission change wrt Diesel	[-]	-	+8%	+14%	-38%	-50%	+27%	-5%	+7%	-19%

Table A1.6  
Direct pollutant emissions regarding the selected bus powertrains. Diesel buses are characterised in terms of their environmental classification.

uom	Diesel						Alternative technologies					
	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI	CNG	LNG	BEB	FCEB	Hybrid (e + H <sub>2</sub> )	
PM2.5	[g/km]	0.484	0.222	0.209	0.047	0.047	0.002	0.004	0.004	0	0	0
CO	[g/km]	2.736	2.463	2.695	0.225	0.225	0.225	0.78	0.78	0	0	0
NOx	[g/km]	10.195	10.801	9.469	5.471	3.119	0.603	1.949	1.905	0	0	0

(-4% GHG emissions with respect to Scenario E) and local (almost -20% PM<sub>2.4</sub>, CO and NO<sub>x</sub> emissions with respect to Scenario E) environmental impacts. On the contrary, scenarios presenting a share of natural gas - based powertrains increase both GHG and local direct pollutant emissions with respect to scenarios considering only diesel bus investments.

#### 4.4. Multicriteria decision matrices results

Life-cycle cost and environmental analysis results for both the urban and the ex-urban scenarios are summarized in the multicriteria decision matrices reported in Table 6 and Table 7 respectively.

For the urban context and with a long-term vision (2033), Scenario A, C and C.bis are the non-dominated ones. The latter consisting in investing only in new battery electric buses appears to have the least impact from an environmental point of view: direct emissions are null and greenhouse gases are lower than other scenarios (-47% if compared to Scenario A, in which only diesel bus investments are foreseen). However, among the non-dominated scenarios, this has the worst economic performance with a discounted life cycle cost of 99 mln€ (about +30% compared to Scenario A). On the contrary, scenarios involving the introduction of natural gas-powered vehicles are dominated by Scenario A: this is due to higher economic costs (up to +10%, mainly due to infrastructure and investment costs), higher GHG emissions (up to +8%) and local pollutants. Likewise, scenarios characterized by investments in FCEB (D and D.bis) are dominated respectively by Scenario C and C.bis: in addition to more expensive vehicle investment and power costs, GHG emissions are also significantly higher (+40% or +95% for a more or less gradual transition).

For the ex-urban context, Scenario E and G are the non-dominated ones: the first has the best economic performance (i.e. lower discounted life cycle costs), while the second has the best environmental one (i.e. lower emissions). Particularly, the introduction of Hybrid (e + H<sub>2</sub>) buses in the long run would reduce GHG and local pollutant emissions respectively by 4% and 20%, despite a +16% in discounted life cycle costs if compared to Scenario E. Also in this context, scenarios involving the introduction of (liquefied) natural gas-powered vehicles are dominated by Scenario E: the increase in economic costs (up to +6%) is coupled with both higher GHG (up to +14%) and local pollutant emissions with respect to the introduction of diesel buses only.

## 5. Discussion

Results related to the urban context have shown that the “full-electric” scenario (i.e., investing only in new BEBs) appears to have both the least environmental impact and the worst economic performances, confirming findings from other studies comparatively exploring different bus technologies (García et al., 2022; Mao et al., 2021). However, it should be underlined that, regarding DLCC calculation, current market prices have been assumed in this analysis and BEB market could offer more advantageous purchase opportunities in the near future (i.e., lower prices for BEBs making them competitive with current diesel bus prices) (Berckmans et al., 2017). Moreover, a gradual (i.e., slower over time) introduction of BEBs would guarantee cost savings (9%), increasing GHG emissions by 36% with respect to a fast transition. It is worth mentioning that absolute DLCC values, and therefore percentage variations, could be exacerbated by considering other cost items. For example, costs related to the upgrading of the local electricity grid that would be necessary to overnight charge a large number of buses would lead to different numerical results (note that this cost item was not taken into consideration as it was assumed in charge of the energy supplier, and not of the LPT Agency). The same happens for civil work costs that would be necessary in case of extra-space needed in the depot to accommodate electric charging stations (it was evaluated as not relevant with reference to the considered case study). Scenarios envisaging the introduction of fuel-cell hydrogen buses resulted to be

dominated: a fast FCEB introduction is characterized by higher discounted life-cycle costs (+48%), both for the vehicles and the energy carrier (as shown also in (Bekel and Pauliuk, 2019)), and by higher GHG emissions (+98%) than a fast BEB introduction (as resulted in (Joshi et al., 2022)). This environmental outcome is mainly due to the equivalent CO<sub>2</sub> released during the hydrogen production phase (Well-to-Tank), especially in the medium term where this process is combined with a CO<sub>2</sub>-intensive electricity production (see electricity grid carbon intensity assumptions in Table 2). The same happens for the introduction CNG buses: both gradual and fast CNG transitions are dominated as they worsen both the economic (up to +10% DLCC) and environmental (up to +8% GHG emissions) impact with respect to a business-as-usual scenario, conservatively investing only in new diesel buses. This result is in line with those from previous studies, for instance (Sharma and Strezov, 2017; Armaroli et al., 2022).

For the ex-urban service, instead, there is still uncertainty about the most suitable decarbonizing technology. Particularly, long-range BEBs having sufficient battery autonomy to guarantee efficient operations on medium-long distance routes are not yet widely marketed. As industrial research and development continues, the introduction of Hybrid (e + H<sub>2</sub>) buses would allow to bypass this limit while ensuring GHG and local emission savings (4% and 20% respectively, in our case study) in relation to traditional diesel buses. However, buses equipped with electric engines (BEB, FCEB or Hybrid e + H<sub>2</sub>) are still not competitive in price compared to diesel ones: a cheaper alternative can be the use of LNG buses, but this analysis highlighted a worse environmental performance compared to current diesel buses (Sharma and Strezov, 2017; Armaroli et al., 2022). Note that this result is limited to standard LNG considered in this study: a new perspective could be considering bio-LNG, therefore improving environmental performances for this energy carrier (Alamia et al., 2016).

## 6. Conclusions

To contribute to the bus fleet decarbonization debate, this paper presented a multicriteria based assessment method drawn up upon the economic (i.e., life-cycle costs) and environmental (i.e. GHG and local pollutant emissions) one. The application of this method led to the comparison of different scenarios through a multicriteria decision matrix. Each scenario was characterized by different sets of investments in clean-fuel buses and, with reference to the Italian basin consisting of the provinces of Como, Lecco and Varese, the aim was to identify the non-dominated ones for both the urban and the ex-urban LPT context, with an overall long-term vision (i.e. 2033).

With reference to the case study, results show that a transition to BEBs is the most promising for an environmental-friendly urban bus fleet. LPT agencies and operators must set the basis for this shift, investing also in the training of their workers who will have to deal with different than now engines (i.e., electric engines instead of internal combustion ones). At the same time, public transport planners and environmental agencies need to set realistic global and local pollutant reduction targets for the LPT service, in line with the financial resources available to support fleets transition: a more gradual target achievement should be considered in the case of binding financial constraints. Contrary to the urban context, there is still uncertainty for the ex-urban one: public bodies should help finance the research and development of economically and ecologically sustainable long-range buses to better clarify long-term LPT ex-urban service transition perspectives.

Among the limitations of this research, it is worth mentioning that results are case specific and are not directly transferable to other contexts, as they are strictly dependent on variables such as the distribution by age and by power train of the current bus fleet, the current line routes, or the investments already planned and programmed. However, this is no longer true for the proposed methodology: among its strengths, it considers local transport context related attributes and has the advantage of being easy to be replicated by other LPT agencies to

identify their most sustainable bus fleet renewal pathway. It is also worth to outline that the costs considered in this analysis are only the financial expenditures of LPT Agencies for bus acquisition, maintenance, operations and other investment, whereas both global and local pollutant reductions may have relevant indirect economic impact on human lives (also monetizable, following the cost-benefit analysis assessment approach (Boardman et al., 2017; Delft et al., 2020)) that have not been taken into account in this study.

Regarding the methodological approach and its application, future research could complement it with a stakeholder engagement phase aiming at understanding the importance in the decision-making of each economic and environmental assessment criteria: this would allow to generate an all-in-one indicator (consisting of a calibrated weighted average of each considered assessment criteria), identifying both urban and ex-urban LPT service optimal transition pathway. Moreover, as the market evolves, a possible follow-up to this study could evaluate different transition scenarios including new bus technologies (for instance, long-range BEB) or new energy carriers (for instance, biodiesel or biomethane) to be considered for less pollutant LPT service. In addition, focusing on BEB, the impact of different charging strategies (for instance, opportunity charging at depots or at stops) on both the economic and environmental performance could be evaluated.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Annex.

The current annex contains the inventory data and the parameters used to perform the LCA environmental analysis.

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