TECHNOLOGICAL, ENVIRONMENTAL, AND ECONOMIC ANALYSIS OF THE HYDROGEN CONVERSION OF A CITY BUS FLEET

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ABSTRACT

The transportation sector plays a critically important role in the current global debate on the need to reduce emissions to address the challenges related to urban pollution and climate change. In the European territory, transportation is responsible for up to a quarter of the total carbon dioxide emissions due to private road transport and public services. In this context, the development and modernization of local public transport (LPT) services can fundamentally contribute. Solutions and less polluting technologies to renew the LPT vehicle fleet and improve service quality to increase attractiveness can contribute to lowering emissions, shifting users from private to public transport, reducing traffic, and improving air quality. Due to the duty cycle and rangeability, fully electric solutions could not be employed to replace the standard LPT vehicles completely. In this context, hydrogen-powered buses can represent a valid alternative.

The present analysis focuses on studying hydrogen-powered buses, which could provide a viable zero-emission alternative to vehicles powered by fossil fuels. Hydrogen can also play a complementary role in battery electric vehicles and hybrid vehicles, moving toward the goal of zero emissions due to the transport of passengers. The objective of the present study is to evaluate the effects in both environmental and economic terms of renewing the LPT vehicle fleet by introducing hydrogen buses in a small-to-medium scale city in the north of Italy. Starting from the state-of-the-art existing technologies for the propulsion of hydrogen-powered vehicles by analyzing pros and cons, the local needs in the public transport fleet have been matched to the commercially available hydrogen-powered buses. A specific assessment of the emission between traditional powered buses and hydrogen-fueled scenarios has been done considering multiple scenarios. A final evaluation of how fleet renewal through adopting hydrogen buses might impact emissions and costs on the environment and the municipal budget has been discussed.

1 INTRODUCTION

The transportation sector plays a critically important role in the current global debate on the need to reduce emissions to address the challenges related to urban pollution and climate change. The electrification of personal vehicles is not sufficient to meet the emission requirements. Due to this, hydrogen and electric buses will be used to replace conventional buses, reducing the emissions per unit per person (Logan et al., 2020). At the same time, by replacing the traditional (diesel) buses with hydrogen-fueled buses and looking at the mid-term scenario (2030) considering the scale-up of the technology, hydrogen buses could reduce the total cost of ownership, increasing their usage for the public transport in the small and midsize city (Kim et al., 2021).

In the Italian territory, most of these are due to private road transport (ISPRA, 2023). The National Integrated Energy and Climate Plan, by the Green Deal, sets as a target for 2030 a 33 % reduction in emissions of greenhouse gas emissions from the transportation sector. To pursue this goal, the national

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framework promotes using alternative fuels, particularly electricity, natural gas, and hydrogen (MASE, 2019).

About 95 % of hydrogen is produced from fossil sources, emitting high amounts of CO_2 into the atmosphere (Qureshi et al., 2023). Hydrogen is classified according to the production method used by color coding. Gray hydrogen refers to that produced from hydrocarbons. The most used method is steam reforming of natural gas. During the production of Gray hydrogen, high amounts of CO_2 are released. Blue hydrogen is also produced from fossil fuels, and the CO_2 emitted is captured, stored, and then used for other industrial processes. Finally, Green hydrogen is obtained through electrolysis, a technology that uses electricity to split water molecules into oxygen and hydrogen. The electricity used to produce Green hydrogen comes from renewable sources, which is currently the most sustainable method. There are other ways to produce hydrogen in a renewable way, such as photolysis (using sunlight to break down water molecules) or the use of biological processes and algae. However, these processes are uncommon as they still are in their infancy (Aminudin et al., 2023; Qureshi et al., 2023).

Interest in hydrogen for vehicle propulsion has grown in recent years because its combustion does not produce CO_2 and because of its energy content. Hydrogen has a lower calorific value of 120 MJ/kg, which is much higher than that of other fuels (for example, that of methane is about 50 MJ/kg, while that of gasoline is 44 MJ/kg). However, because of its very low density (the density of hydrogen is 13 times less than that of air), the energy content per unit of volume of hydrogen is much lower (about 11 MJ/m^3 vs. 32 MJ/m^3 of methane). For this reason, it requires either very large reservoirs or high storage pressures (Dawood et al., 2020). Although even electric buses can provide a zero-emission alternative, they are penalized by the presence of a heavy battery pack, a relatively low range, and long charging times (Correa et al., 2017). The ability to refuel entirely in just a few minutes and the high autonomy make hydrogen-powered propulsion units an attractive option in public transportation. At the same time, the investment required to purchase fuel cell buses is the main obstacle that slows their diffusion and adoption to date. An example of such an obstacle is the *Montpellier Horizon Hydrogen* project, which included purchasing fuel cell buses. However, due to their high cost, the municipality has changed the target to fully electric buses (battery-powered) (Sustainable bus, 2023).

Electrolysis is an energy-consuming process; to produce 1 kg of hydrogen from an electrolyzer with an efficiency of 60 %, about 55 kWh of electrical energy is required. To use hydrogen inside a vehicle, after being produced, it must be compressed, transported, and finally converted back into electricity via a fuel cell to power an electric motor with an efficiency of (55-60) %. This means that by starting with the input of electricity for the electrolysis of water to produce hydrogen and then using that hydrogen in a fuel cell to generate electricity, the recovery of the initial energy is about 30 %. Literature data shows how the environmental effectiveness of fuel cells for powering city buses depends strongly on the energy generation used to produce hydrogen (renewable sources determine the effectiveness of their application), as reported by Vodovozov et al. (2022). Hydrogen production (especially green hydrogen) and the refueling station are the biggest challenges in the next years (Wijayasekera et al., 2024). In Table 1, the well-to-wheel (WTW) efficiencies of various types of vehicles are shown. The WTW considers all energy losses from fuel extraction to the vehicle wheel, including losses due to refining, distribution, etc. (Zhang et al., 2015).

1.1 Aim of the investigation

The objective of the study is to evaluate the effects in both environmental and economic terms of renewing the LPT vehicle fleet through the introduction of hydrogen buses. This analysis aims to estimate the current fleet's emissions and evaluate the environmental and economic impact of purchasing hydrogen-powered fuel cell buses. Starting from the actual scenario, the assessment comprises the emission budget estimation related to bus replacement and an analysis of the specific cost [€/km] related to the bus mileage.

2 PROPULSIVE SYSTEMS AND THEIR PERFORMANCE

Currently, there is no single technology that can meet all the criteria of economic, performance, and environmental. Different technologies must operate in a complementary manner to each other. Current technologies that enable hydrogen to be harnessed for automotive use include internal combustion engines and fuel cells or fuel cells. In the former, hydrogen is burned alone or together with other fuels

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Table 1: Comparison of the WTW efficiency for Internal Combustion Engine (ICE), Battery Electric Vehicle (BEV), and Fuel Cell Vehicle (FCV) (Zhang et al., 2015)

Energy source	Fuel type	Fuel production [%]	Propulsion type	Distribution [%]	Refueling [%]	WTW [%]
Fossil	Gasoline	86	ICE	98	99	25
Fossil	Diesel	84	ICE	98	99	29
Renewable	Electricity	100	BEV	90	-	61
Renewable	Electricity ->H_2	68	FCV	89	90	30

by exploiting an Otto or Diesel cycle, precisely as occurs in a conventional engine (Boretti, 2020, Boretti and Watson, 2009, Gomes Antunes et al., 2009, and White et al., 2006). Due to the high temperature reached in the combustion chamber, emissions of NOx are about 20 % higher than in a gasoline engine (Wróbel et al., 2022).

Another avenue being explored to reduce pollutant emissions is that of bi-fuel-powered buses. This consists of installing a system similar to those existing on the vehicle (e.g., methane), which works with hydrogen. Hydrogen is injected in small percentages (between 5% and 20%) along with the traditional fuel (diesel or gasoline). This solution improves combustion, lowers pollutant emissions and fuel consumption, and increases engine efficiency (Dimitriou and Tsujimura, 2017). Bi-fuel technology is particularly interesting for those sectors that exploit diesel engines extensively (e.g., road freight transport, marine industry, earthmoving) and which it is not possible to convert to electric, as the weight of the batteries and the recharging time required is not compatible with the needs of these sectors.

Fuel cell operation is based on an electrochemical reaction between hydrogen and oxygen. This reaction produces electrical energy, while heat and water are waste elements (Manoharan et al., 2019). An FCV is thus essentially an electric vehicle in which electricity is produced onboard starting from liquid or gaseous hydrogen. There are different types of fuel cells, but they are all based on similar operations. The various types are differentiated according to the electrolyte used (Manoharan et al., 2019).

While hydrogen-powered internal combustion engines emit high amounts of NOx (as much as 20 % more than conventional gasoline engines) and also, even if low, CO_2 emissions, fuel cells emit only water as a waste element and, therefore, are more suitable as powertrains if the goal is to lower harmful emissions, especially in urban environments. Despite these superiorities of fuel cells over combustion-based systems, they also have penalizing features summarized as follows:

- hydrogen purity: fuel cell requires hydrogen with a purity level greater than 99.9 % (Aminudin et al., 2023);
- maturity of the technology: fuel cells exploit a relatively new technology, and thus, the CAPEX costs are very high, up to 3 times more than an equivalent heat engine (Ajanovic et al., 2021);
- presence of rare metals: platinum is used in fuel cells as a catalyst to accelerate the oxidation-reduction reaction. The estimated production of platinum in 2022 is 190 tons (Statista, 2023), and considering that each fuel cell requires 20 to 40 g of platinum (Manoharan et al., 2019), if all the platinum mined in a year were used for vehicle production, about 6.3 M vehicles would be built, which corresponds to 0.43 % of the vehicles in the world.

3 HYDROGEN BUSES

There are various configurations for hydrogen buses. The first configuration shows a schematic of a bus driven by an internal combustion engine powered by hydrogen. This configuration is the same as that used for classic buses with an endothermic. The second configuration uses a fuel cell, which produces electricity that directly powers an electric motor that provides traction. This scheme was most commonly used in the early hydrogen bus models, but it was later supplanted by the configuration represented by the third scheme. In the third configuration, a battery with an accumulator function was introduced. The fuel cell produces electrical energy to recharge the battery; the latter is responsible for powering the electric motor. In this way, the fuel cell does not directly power the engine but extends the range by charging the battery. The latter configuration is currently used by manufacturers. It has a twofold advantage related to the regenerative braking and additional power supply (instantaneous power

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generated by the fuel cell may not be sufficient).
Regarding vehicle refueling, LPT companies that use hydrogen-powered vehicles usually build storage facilities near their depot. Hydrogen is produced on-site through electrolysis or transported through hydrogen pipelines. The characteristics of the European refueling stations are given in Ajanovic et al. (2021) and Qureshi et al. (2023).

3.1 Pollutant emissions from buses

The database of emission factors is based on estimates that are developed, taking into consideration national data regarding the fleet and circulation of vehicles, including number of vehicles, mileage, average fuel consumption, average speeds, and other parameters. Emission factors are calculated using COPERT (Computer Programme to calculate Emissions from Road Transport), the software developed by the European Environment Agency. The methodology is based on (EMEP, 2019), and the data are updated to 2020. Table 2 shows the ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) and ADEME (Agence de l'Environnement et de la Maîtrise de l'Énergie) (for CNG buses) emission factors. For CNG buses, only those of the latest generation were considered due to a lack of information regarding older CNG buses. The working cycle considered is the urban cycle.
These coefficients are the same as those used by the National Strategic Plan for Sustainable Mobility (NSPSM). The only coefficients that do not come from ISPRA sources are those concerning the CNG buses; these are subject to significant uncertainty because of the few tests on the road. For this reason, the coefficients proposed by ADEME are used for CNG buses. The NSPSM chooses these coefficients as they are considered more reliable for CNG buses (MASE, 2019).
As seen from Table 2, the latest generation of CNG buses generally have pollutant emissions lower than the Euro 6 bus, except for carbon monoxide (CO). Hybrid buses have lower emissions than Euro 6. Comparing hybrid buses and CNG buses, the former has much higher PM10 emissions than CNG buses, while for other pollutants, they have lower or comparable coefficients. For CO_2, separate considerations need to be made. All diesel buses have similar CO_2 emissions. Hybrid buses have CO_2 emission coefficients about (25-30) % lower than CNG and Euro 6 buses. The latest generation Euro 6, CNG, and hybrid buses significantly reduce harmful emissions, favorable for air quality and the related impacts on human health. In contrast, the reduction in CO_2 emissions is more modest.

4 CASE STUDY

The present analysis focuses on Ferrara's bus fleet. This scenario is representative of a small-to-medium-scale city located in the north of Italy.

4.1 Bus fleet characteristics

Ferrara's public transportation service is operated by TPER (Trasporto Passeggeri Emilia Romagna). The current bus fleet comprises 261 vehicles: 60 used in urban areas, 21 in suburban areas, and 180 in out-of-town routes. The fleet includes 70 % diesel-powered vehicles, 30 % CNG vehicles, and a residual portion of hybrids. The local utility plans to replace the most obsolete vehicles with more technologically advanced ones to reduce the polluting emissions produced by the LPT.
Hydrogen-powered vehicles will, therefore, complement other zero-impact traction modes. The

Table 2: Emission coefficients from ISPRA and ADEME (MASE, 2019 and EMEP, 2019) for an urban cycle

Type	PM10 [g/km]	NOx [g/km]	CO [g/km]	CO_2 [g/km]
Hybrid	0.11	0.29	0.16	681
CNG	0.001	0.24	0.89	921
Euro 2	0.31	11.51	2.41	1’007
Euro 3	0.31	10.19	2.69	1’056
Euro 4	0.16	6.25	1.29	984
Euro 5	0.20	7.00	2.23	949
Euro 6	0.12	0.49	0.27	967

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decision to introduce hydrogen-powered buses stems from their greater flexibility and autonomy compared to battery-electric vehicles. The refueling time, much less than the several hours required to recharge a battery electric bus fully, allows the potential use of fuel cell buses on medium- and long-distance routes. Hydrogen fuel cell buses will be introduced in urban areas to replace the current diesel and CNG-powered buses. Therefore, the criteria for replacing traditional buses are related to the selection of fuel cell buses corresponding to the latter configurations explained in the previous section. Currently, the *urban* fleet consists mainly of CNG buses (48 %), hybrid buses (32 %) and diesel buses (20 %). The goal for 2028 is to reduce the presence of diesel buses to zero, decrease the presence of CNG buses to 18 %, keep the percentage of hybrids constant (32 %), and introduce electric (13 %) and hydrogen (37 %) buses, as shown in Fig. 1.

4.2 Actual scenario

The emissions of the current fleet are reported in Tab. 3. They were calculated using the emission coefficients shown in Tab. 2 multiplied by the bus mileage. The data were provided by TPER and are related to the first half of 2021.
Resembling the data reported in Tab. 3 to cover a reference year, the actual fleet performance (in terms of emissions) can be calculated. The pie charts shown in Fig. 2 summarize the actual scenario. The data show that harmful emissions (PM10, NOx, CO) are mainly due to the older Euro 2 and Euro 3 buses, even though these account for only 25 % of the total mileage. Considering NOx emissions, Euro 2 and Euro 3 buses account for 65 % of the emissions. Besides harmful pollutant emissions, Euro 2 and Euro 3 vehicles also produce 46 % of PM10 emissions and 51 % of carbon monoxide. Unlike the other types of emissions analyzed previously, for $CO_{2,}$ there is no particular difference in incidence according to vehicle category. From this data, replacing old buses with new-generation vehicles (fueled by fossil fuel) is insufficient if the goal is to decrease the carbon dioxide emitted into the atmosphere.

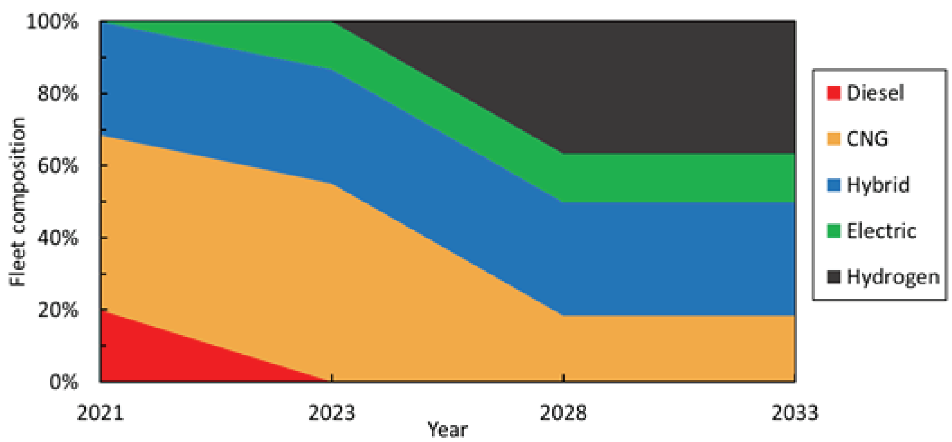

Figure 1: Evolution of vehicle fleet in urban areas (elaboration on TPER data)

Table 3: Pollutant emissions from buses in the first semester of 2021 (elaboration on TPER data)

Type	Mileage [km]	Ratio [%]	PM10 [kg]	NOx [kg]	CO [kg]	CO_2 [kg]
Hybrid	762’606	15	84	221	122	519’395
CNG	536’591	11	1	54	478	494’200
Euro 2	546’726	11	169	6’293	1’318	550’362
Euro 3	726’170	14	225	7’400	1’953	767’003
Euro 4	149’446	3	24	934	193	146’990
Euro 5	842’196	17	168	5’895	1’878	799’193
Euro 6	1’499’351	30	180	735	405	1’450’128
Total	506’3086	100	851	21’531	6’346	4’727’272

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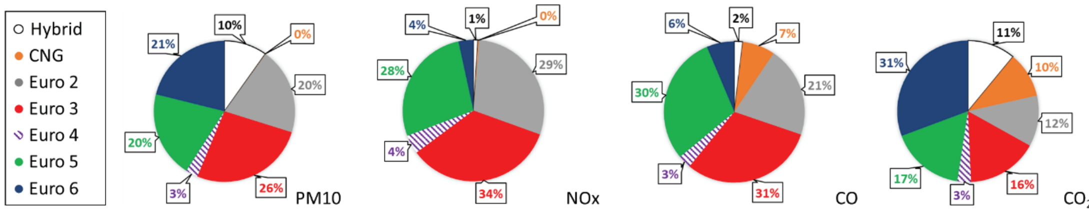

Figure 2: Incidence of emissions by vehicle type

5 EMISSION COMPARISON BY FUEL TYPE

To determine whether it is cost-effective to use fuel cell-powered buses from the perspective of emissions, it is necessary to compare the emissions produced by vehicles powered by fossil fuels with those produced by hydrogen-powered vehicles. Using the coefficients reported in Tab. 2, it is possible to calculate the savings in emissions that would result from replacing older vehicles (Euro 3) with more technologically advanced buses (Green hydrogen, hybrid, CNG, and Euro 6 powered buses).

5.1 CO_2 emissions

In Tab. 4, the emission estimates *e* for the various fuels, including *green* and *gray* hydrogen are reported. Green hydrogen, produced by electrolysis from renewable sources such as photovoltaics and wind power, makes no atmospheric emissions. However, an emission factor *e* of 0.7 kg CO_2/kgH_2 due to the compression of the gas (Lozanovski et al., 2018) is considered. According to Ajanovic et al. (2021), the gray hydrogen's emission factor was assumed to equal 13.2 kg CO_2/kgH_2. An annual mileage *p* of 45'000 km is assumed, comparable to other studies on the subject (Lozanovski et al., 2018). The hydrogen consumption *c* for a 12-meter bus is around 9 kgH_2/100km (Ajanovic et al., 2021). The CO_2 emission per year produced by a hydrogen bus is calculated as

$$E = e \cdot \frac{c}{100} \cdot p \quad [kgCO_2/year] \tag{1}$$

Emissions due to the construction of the bus, the panels, and the electrolyzer are not accounted for (Pederzoli et al., 2022). Similarly, extraction, refining, and transportation operations have not been accounted for fossil fuels. For hydrogen, results vary dramatically depending on the production method. A fuel cell bus powered by gray hydrogen produced by steam reforming produces CO_2 emissions comparable to, if not greater than, Euro 6. If hydrogen is made entirely from renewable sources, there is a reduction in CO_2 emissions of up to 94 %. As might be expected, using an alternative energy carrier such as hydrogen to lower pollution levels only makes sense if its production comes from renewable energy sources. The high emissions from the production of gray hydrogen mean that it is not a viable alternative for developing sustainable mobility. For this reason, only green hydrogen will be considered in the following emissions comparisons. According to the previous analysis, the buses with the highest pollutant emission factors are Euro 2 and 3. Using the emission factors of Table 2, the carbon dioxide emissions that would be avoided by replacing a diesel bus Euro 3 with a fuel cell bus are estimated. Figure 3 shows the amount of CO_2 saved per Euro 3 bus replaced for hydrogen, hybrid, CNG, and Euro 6 buses. In addition, the percentage reduction concerning the Euro 3 scenario has also been reported.

Table 4: CO_2 emissions for different fuels

Type	CO_2 Emission [gCO_2/km]	Emission [kgCO_2/year]
Gray H_2	119 gCO_2/km	53’460
Green H_2	6.3 gCO_2/km	2’835
Hybrid	681 gCO_2/km	30’649
CNG	921 gCO_2/km	41’445
Euro 6	967 gCO_2/km	43’523

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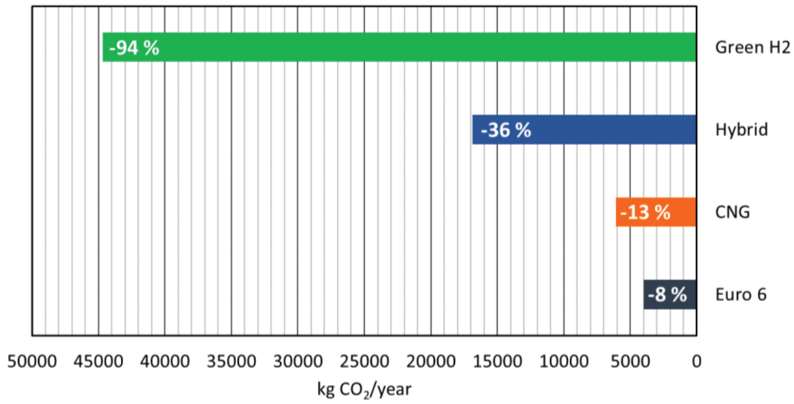

Figure 3: CO_2 saved per Euro 3 bus replaced. The percentage values indicate the reduction with respect to the Euro 3 scenario

Figure 3 shows that among the technologies analyzed, hydrogen is the one that allows the greatest reduction of carbon dioxide emissions. The TPER's plan calls for introducing 22 hydrogen-powered buses by 2028, resulting in emission savings of about 990 t of CO_2 per year.

5.2 Pollutant emissions

Using the same method as the previous analyses, it analyzed the savings in harmful emissions by replacing a Euro 3 bus. Figure 4 summarizes the results by reporting the amount of pollutant emissions saved per Euro 3 bus replaced and the percentage reduction concerning the Euro 3 scenario. In this case, the difference in emission savings between the various technologies is much less pronounced. Green hydrogen does not emit harmful substances in its production, and its use remains the fuel that reduces the most emissions, even if the difference with other state-of-the-art technologies is minimal. The latest generation vehicles (Euro 6, hybrid, or CNG) incorporate technologies that have substantially reduced harmful emissions. These technologies include exhaust gas recirculation systems, treatment, and particulate filters. Combined with continuous research on improving internal combustion engine combustion and thermal efficiency, these technologies have reduced emission factors. While significant progress has been made in enhancing harmful emissions, the same cannot be said of CO_2 emissions. This is because carbon dioxide emission is an inevitable consequence of burning fossil fuels such as diesel and methane. The comparison of diesel vehicles under the various Euro regulations shows that harmful emissions have dropped dramatically while CO_2 emissions have remained unchanged (see Fig. 3).

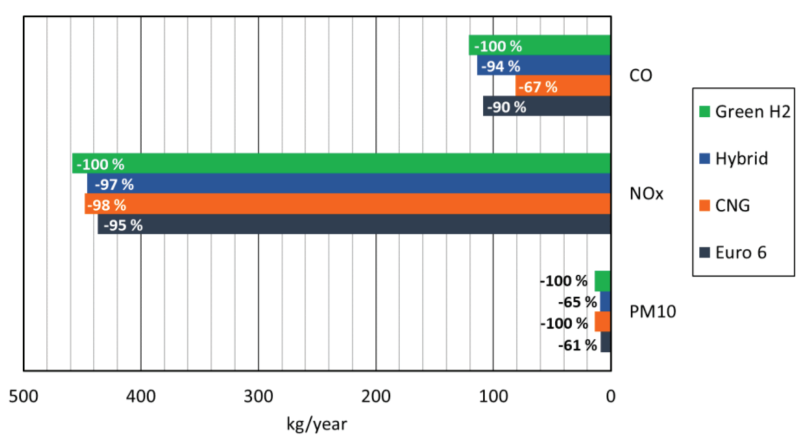

Figure 4: Pollutant emissions saved per Euro 3 diesel bus replaced. The percentage values indicate the reduction with respect to the Euro 3 scenario

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6 COST ANALYSIS

The main obstacle to adopting hydrogen buses is their high cost compared with diesel, CNG, or electric buses. In addition to a high purchase cost, hydrogen vehicles are also penalized by the high fuel cost. This section assessed the cost per kilometer for the considered technologies. Firstly, the cost calculations were performed for the *reference* case, and then, different scenarios (by changing the annual mileage and purchasing cost) were proposed to determine whether a hydrogen bus can be a viable alternative to a conventional vehicle in terms of cost.
The parameter used for the cost analysis is the total cost ownership (TCO). It is an indicator for evaluating the total costs associated with an asset's purchase and use throughout its operating life cycle. The TCO takes into account direct and indirect costs. In the case of purchasing a hydrogen-powered bus, the main components of TCO are the purchase of the vehicle, the purchase of the fuel, and routine and extraordinary maintenance. To evaluate costs and compare different technologies with each other, costs will be expressed in [€/km]. The TCO is assessed by considering the cost of purchasing the vehicle (C_a), the cost of fuel (C_c), and maintenance costs (C_m) related to the distance traveled in a year (p), according to

$$TCO = \frac{C_a\,\alpha}{d} + C_c + \frac{C_m}{p} \quad [€/km] \tag{2}$$

where α is the recovery factor to account for the annual rate of the loan interest defined as

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

where i is the interest rate, and n is the number of years in which the loan. To estimate costs, it is necessary to include literature data and reliable assumptions. All the data are summarized in Table 5. The cost of a diesel bus ranges from 210'000 € to 250'000 €, while hydrogen-powered buses are much more expensive, varying from 600'000 € to 700'000 € (Ajanovic et al., 2021). The diesel consumption of a bus in an urban cycle is between 25 l/100km and 35 l/100km, while fuel cell-powered buses are assumed to consume 9 kgH_2/100km (Ajanovic et al., 2021). The price of diesel fuel was assumed to be 1.3 €/l, while that of green hydrogen ranges from 4.5 €/kg to 7.1 €/kg (IEA, 2023). The maintenance costs for diesel and hydrogen vehicles are very similar and are 0.27 €/km and 0.24 €/km, respectively (Ajanovic et al., 2021). The loan interest rate is 5 %, and the useful life of the buses is assumed to be 14 years (in agreement with Ajanovic et al., 2021) with an annual mileage of 45000 km.
It can be seen from the bar chart in Fig. 5 that the total cost of ownership is much higher for the hydrogen bus than for the diesel bus. The total cost per kilometer of a diesel bus stands at 1.18 €/km, while that of a fuel cell bus is 2.18 €/km. To increase the usefulness of the present analysis, the second analysis refers to an increased mileage per year (from 45'000 km to 90'000 km per year). This scenario could be representative of a bigger city or, at the same time, assess an increased demand for public transport instead of private vehicles. This scenario, reported in Fig. 5, shows that the cost per kilometer is lowered for both types of buses. The fuel cell-powered bus becomes slightly more competitive, but its cost is still higher by 0.55 €/km than the diesel bus. Comparing the data for the diesel-powered bus in the reference case (45'000 km/year) to hydrogen in the new scenario (90'000 km/year), it is interesting to note that even though the latter travels twice the distance than the former, it still has a higher cost per kilometer. To match the cost, the fuel cell-powered bus would have to travel about 3.4 times the distance traveled by the diesel bus, or, in other words, 152'000 km/year.

Table 5: Average data used for cost calculations

Feature	Euro 6	Hydrogen
Purchase [€]	230’000	630’000
Fuel consumption	30 l/100 km	9 kg/100 km
Fuel cost	1.3 €/l	5.8 €/kg
Maintenance cost [€/km]	0.27	0.24

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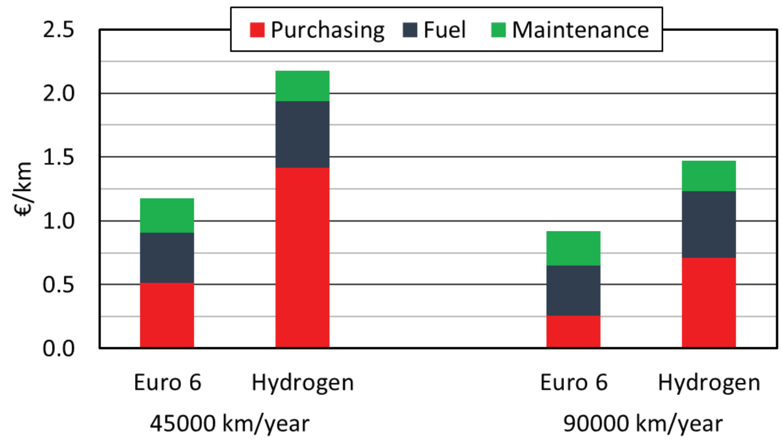

Figure 5: Diesel and hydrogen bus mileage cost, for 45'000 km/year (reference case) and 90'000 km/year

6.1 2050 Scenario

Reducing the purchase cost of fuel cell buses could promote their deployment within local public transport and increase the competitiveness of this technology compared to other low-emission technologies. In 2019, several hydrogen bus manufacturers founded the H2Bus consortium, whose goal is to be able to offer fuel cell buses at a price below 375'000 $ (H2BUS, 2023). It is unknown when it will be possible to reach these cost levels, but we assume this price will be reached by 2050. The International Energy Agency predicts that as early as 2030, the cost of producing green hydrogen from renewable sources will drop significantly, standing at between 1.1 $/kg and 3.3 $/kg (IEA, 2023). To assess the 2050 scenario, it can assume the same mileage (45'000 km/year) and an operating life of 14 years. Given the impossibility of predicting the trend with a reasonable margin of safety, the price of diesel fuel is considered the same as in the base case (1.3 €/l). Based on this scenario's assumptions, the hydrogen bus would cost 1.27 €/km, which is only 0.09 €/km more expensive than the diesel alternative, as reported in Fig. 6.

At the time of writing, hydrogen buses are too expensive to purchase without European and state incentives and funding. The goal of incentives is to accelerate the adoption of green technologies for mobility and simultaneously increase research and development for improved technologies and

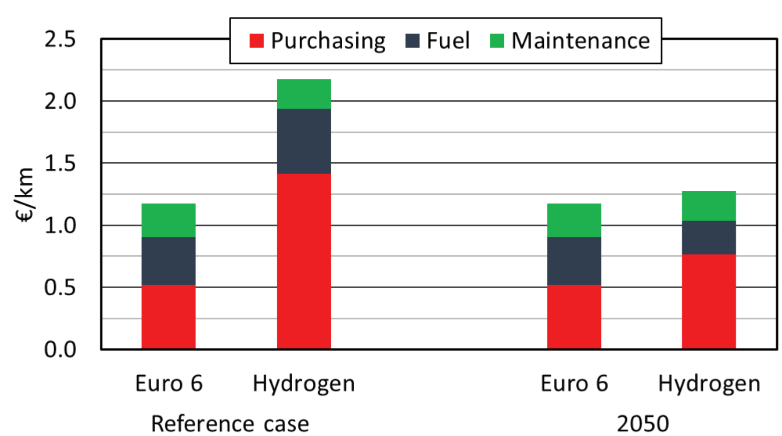

Figure 6: Comparison of base case scenario to 2050

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competition among manufacturers so that in the future, these means of transportation will be cheaper and more easily accessible. Although the TCO of a hydrogen bus is higher than an equivalent diesel, this parameter does not consider the social costs of air pollution. The incidence of respiratory diseases due to air pollution causes increased costs of associated medical, hospital, and pharmaceutical care reflected in the community. A 2020 study commissioned by the European Public Health Alliance uses pollution data from various European cities to calculate the effects of air quality on social costs, considering mortality rates, hospital admissions, lost work days, and other factors. The total cost for the 56 Italian cities is about 21 B€, while the cost per capita is 1'535 € (Delft, 2020).

7 CONCLUSIONS

The analysis shows how replacing diesel buses with fuel cell buses, if powered by green hydrogen, can significantly save CO_2 and harmful emissions emitted into the atmosphere. Even the latest generation of vehicles (Euro 6, CNG, hybrids) powered by fossil fuels have achieved very low harmful emission coefficients compared to Euro 3 and earlier diesel buses. However, the combustion of fossil fuels inevitably emits CO_2, so these vehicles run counter to efforts to decarbonize the transportation sector. Factors that will determine the success or otherwise of these technologies include the development of a suitable refueling infrastructure, the price of hydrogen at the pump, and the necessary purchase cost.

Both hydrogen solutions (fuel cell and internal combustion engine) produce zero or near-zero CO_2 emissions during use. In contrast, endothermic hydrogen engines have the disadvantage of emitting NOx, although this can be limited (exhaust gas recirculation). Internal combustion engine solutions enjoy initial purchase costs much lower than their counterparts, allowing greater versatility at the expense of lower efficiency and, thus, higher fuel consumption.

Zero-emission powertrains should not be seen as competing with each other but rather as complementary technologies that enable diversification of the vehicle fleet and accelerate the process toward zero emissions in the transportation sector. This highlights that zero-emission technologies in local public transport must be accompanied by a change in urban mobility patterns, encouraging the abandonment of private transport in favor of public transport as much as possible. Several factors, such as the rigidity of schedules and routes and user needs, hamper the choice of public transportation. The current high investment costs of replacing transport vehicles powered by fossil fuels with zero-emission vehicles could be partly justified by a positive effect on population health that can translate into significant savings in long-term health care costs.

NOMENCLATURE

ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie	
BEV	battery electric vehicle	
COPERT	Computer Programme to calculate Emissions from Road Transport	
C	cost	(€)
c	hydrogen consumption	(kgH_2/100 km)
CNG	compressed natural gas	
e	emission factor	(kg CO_2/km or kg CO_2/kgH_2)
EMEP	European Monitoring and Evaluation Programme	
FCV	fuel cell vehicle	
i	interest (referred to loan)	(%)
ICE	internal combustion engine	
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale	
LPT	local public transport	
MASE	Ministero dell'Ambiente e della Sicurezza Energetica	
n	number of years	(year)
NSPSM	national strategic plan for sustainable mobility	
p	mileage per year	(km/year)
TCO	total cost ownership	
TPER	Trasporto Passeggeri Emilia Romagna	
WTW	well to wheel	(%)

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α	recovery factor	(-)

Subscript

a	purchasing (referred to cost)
c	fuel (referred to cost)
m	maintenance (referred to cost)

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