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Comparative analysis of cost, emissions and fuel consumption of diesel, natural gas, electric and hydrogen urban buses

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ABSTRACT

Within the context of the energy transition, there are several alternatives under study for the gradual replacement of diesel fuel based urban transport vehicles. This paper proposes an answer to the following question: Which bus technology and energy mix is more efficient in terms of cost, energy consumption and greenhouse gas emissions? A method is proposed to compare different urban bus fleet technologies, using an integrated index composed of three indices that measure well-to-wheel energy use, global warming potential in terms of carbon dioxide equivalent emissions, and total cost of ownership. The method is applied to the case of Argentina, from the 2019 scenario to the year 2030, and the results for each index show that, (i) even for the current energy scenario, battery and hydrogen fuel cell buses show a decrease in greenhouse gas emissions; that (ii) today the compressed natural gas bus is a better mean of passenger transport for both urban and intercity uses (it could reduce the carbon dioxide equivalent emissions 10.07% and the total cost of ownership 5.3%); and that (iii) both battery and hydrogen fuel cell vehicles become cost competitive with compressed natural gas and diesel vehicles over the course of the current decade. In addition, (iv) the battery electric bus is shown to become the best option by 2023 and (v) the hydrogen fuel cell bus proves to be the best option from 2027 onwards. The transition of the entire urban bus fleet in Argentina to zero-emission technologies is expected to be beneficial from the point of view of energy consumption, environmental emissions and the economy. If transition of the whole fleet to Hydrogen fuel cell buses is carried out, 1.3 Mt of carbon dioxide equivalent emissions could be reduced, which represents a 87% reduction in green house gases emissions, and if the transition is to battery electric buses, the energy consumption would be reduced by between 25 and 38% and emissions by between 52 and 61% abating around 0.93 Mt of carbon dioxide equivalent per year.

1. Introduction

Energy transition has become a necessity to mitigate the adverse effects of human activity and the consequent global warming. In 2019, transportation accounted for 54,9% of the world's oil consumption. Particularly in Argentina, vehicles emit 50.18Mt of carbon dioxide equivalent greenhouse gas per year [1].

Urban passenger transport fleets require to be renewed periodically, thus presenting an opportunity to reduce environmental and noise pollution in cities [2]. In the public transport sector, it is likely that new technologies will eventually replace the diesel buses, although the conversion of the traditional transport system seems to be one of the most difficult aspects of the energy transition [3]. Currently, internal combustion engine vehicles (ICEVs) are the most widely used, but trends

Abbreviations: BAT, Battery; BEV, Battery Electric Vehicle; CAPEX, Capital expenditure; CNG, Compressed natural gas; CNGV, Compressed natural gas vehicle; DV, Diesel vehicle; FC, Fuel cell; FCHEV, Fuel cell hybrid vehicle; FCS, Fuel cell system; GHG, Greenhouse gases; ICE, Internal combustion engine; ICEV, Internal combustion engine vehicle; NG, Natural Gas; SOD, State of discharge; TTW, Tank to wheel; WTT, Well to tank; WTW, Well to wheel.

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indicate that by 2030 the majority of new vehicles will be electric [4]. Interest in electric vehicles has increased rapidly in recent years, with more than 2 million such vehicles sold worldwide in 2019 [4]. Among clean technologies for transportation, hydrogen fuel cell electric vehicles have advanced toward commercialization and both fuel cell buses and vehicles in general have seen widespread deployment in several countries [5]. In Argentina, due to the existing compressed natural gas vehicle (CNGV) infrastructure, switching the urban bus fleet to compressed natural gas (CNG) is an alternative that currently is under study [6]. A comprehensive analysis that takes into account different dimensions is necessary to evaluate the behavior of these new transportation technologies under different scenarios. To characterize the greenhouse gas (GHG) emissions associated with the use of an electric drive vehicle, it becomes necessary to consider the original source of energy, i.e. the electricity mix [7]. In the case of hydrogen, while there is no universal naming convention, color codes are used to identify the source and the processes used to produce it, i.e.: gray when hydrogen produced from hydrocarbons and blue if carbon dioxide (CO_2) capture mechanisms are incorporated, pink when hydrogen is produced from water electrolysis and nuclear energy, and green when hydrogen is produced from water electrolysis and renewables energies [8].

Well-to-wheel (WTW) analysis [9] allows vehicles to be examined when powered by various energy sources and driven along different types of roads. WTW analysis can be broken down into two stages:

1. The well-to-tank stage (WTT) includes the energy costs of extracting, mining, transporting, and processing natural resources to deliver energy vectors.
2. The tank-to-wheel stage (TTW) takes into account the processes that take place in the vehicle powertrain, from the moment the fuel is loaded until it is transformed into mechanical energy and heat.

Due to the complexity of the systems under analysis and the enormous amount of variables at stake, it is necessary to cut down the number of variables to be analyzed, and produce an index that allows the comparison of different options [10–12]. Numerous studies exist in the literature based on WTW analysis that perform a detailed examination of transportation systems and generation pathways applied to different countries. In Ref. [13] a comparative exergy and environmental analysis of the vehicle fuel use in Brazilian context is presented. Liu et al. [14] perform a WTW emissions and energy use analysis to compare two commercial vehicles, a fuel cell hybrid Electric vehicle (FCHEV) and an internal combustion engine Vehicle (ICEV), and show that a FCHEV, even feed by hydrogen from a fossil-based production pathway, consumes less fossil energy and emits less greenhouse gas emissions compared to a conventional gasoline ICEV. A relevant precedent was presented by Mizsey and Newson [15], who compared four combinations of powertrain and fuel processing mechanisms using fossil fuels in a diesel or hybrid engine, or hydrogen from fossil sources; and considering WTW efficiency, GHG emissions and investment costs. Subsequently, explorations based on WTW have been performed by analyzing the total energy efficiency of different systems with different production methods of the energy sources [16,17], balances considering energy and environmental factors [10,11,18–21], or taking into account different driving cycles [22,23]. In addition, it can be found in literature studies on environmental life cycle analysis [24], including environmental and economic life cycle [25] in the transport sector.

This study is carried out within the scope of WTW analysis and is applied to urban passenger buses with four different propulsion systems, powered by their respective energy carriers obtained from different sources. Four different urban bus technologies were considered: diesel and CNG internal combustion buses, lithium-ion battery electric bus, and hydrogen fuel cell powered bus. A general method is proposed to compare the energy, environmental and economic performances of different types of engines and energy carriers using a single multiphysics index. In the WTT stage (SubSection 2.1) different primary energies and routes to produce the energy vectors, all framed within Argentina, are evaluated. Bus energy consumption and emissions (TTW stage, SubSection 2.2) may vary due to driving conditions (congestion, geography, number of stops, etc.) and propulsion configurations (battery autonomy, fuel cell type, etc.) [26]. Dynamic models, along with experimental data from Söderena et al. [27], were used at this stage in two different driving cycles, representative of purely urban driving (Braunschweig cycle) and mixed urban-interurban driving (WHVC cycle). In Section 3, energy consumption, total cost of ownership (TCO) and GHG emissions from energy source to bus operation are computed, and indices that cover energy, economic and environmental aspects of the technology proposal are calculated. The analysis of the integrated index from the three indices permits the comparison between technologies. Finally, using the results of emissions and energy demands, the impact of the transition of the entire fleet of urban passenger buses in Argentina from the current (diesel) buses to lithium-ion batteries and hydrogen fuel cell buses is calculated and discussed. Furthermore, the requirements in terms of the addition of renewable energies is analyzed.

The proposed analysis is intended to answer the following questions:

- What would be the results, in terms of environment, cost and energy, of converting the urban bus fleet to CNG, battery electric propulsion or hydrogen fuel cell?
- What conditions must be in place for alternative buses to become competitive with traditional diesel buses?
- What changes in the energy mix are necessary to effectively reduce greenhouse gas emissions from an electrified fleet?

In this paper, the results of a model and its projection for the next decade using an index that considers energy efficiency, capital and operating costs, and greenhouse gas emissions are presented. This model allows performing a well-to-wheel analysis applied to urban buses for two different driving cycles and four different engine types in Argentina, serving as a model for its application to other countries in the region. This study is extremely complex and requires the organization of a large amount of data for each analysis, which is why it is of great importance to establish a global parameter that allows understanding and individualizing the effect of each parameter on the global index for each technology, even more so when seeking to project the study into the future. Finally, all the calculation methods are presented in detail, allowing the reproduction of the analysis considering different weights in each index, different bus fleets, technologies, etc., making this study a tool in itself for other future works.

2. Methods

The methods used in this work are based on the description of the individual discrete processes, considering the energy used, the costs associated with the investment and operation of each technological option, and the gaseous emissions to the environment. In the present study, the methods previously developed in Ref. [11,10], are applied to the energy efficiency analysis. For the WTT analysis, the proposed starting scenario is the production of all energy vectors in Argentina in the year 2019, the most recent with complete records published at the time of this study. Future scenarios up to the year 2030 for electricity generation are based on a document prepared by the Argentine Ministry of Energy and Mining in the year 2019 [28].

In each stage diesel fuel, CNG, compressed hydrogen (GH_2) and electricity were considered as energy vectors for the buses. Fig. 1 shows the primary energy sources, the transport and distribution process, and the relevant fuels and energy carriers to supply all propulsion systems used, providing a visual depiction of the routes to be analyzed in SubSection 3.4.

In the TTW stage, four power trains, using the energy vectors analyzed in the WTT stage, are proposed for urban passenger transport buses:

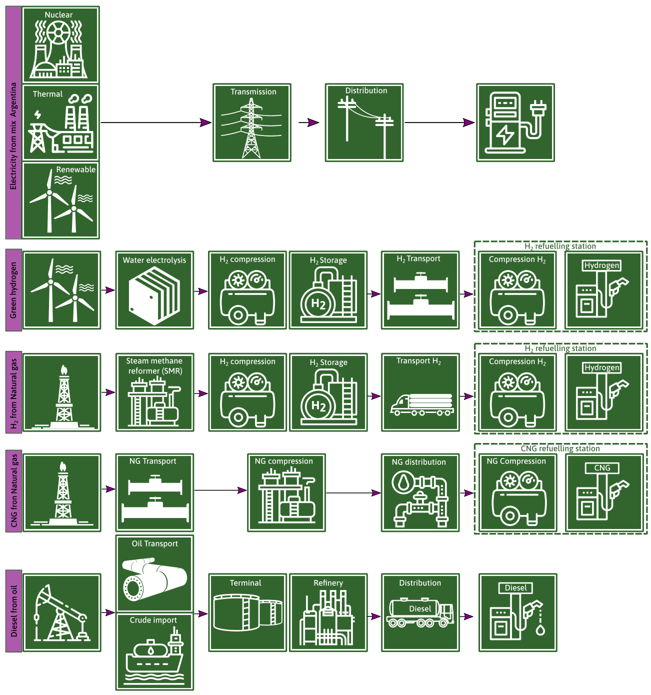

Fig. 1. Energy vectors pathways for the generation, transmission, distribution and delivery.

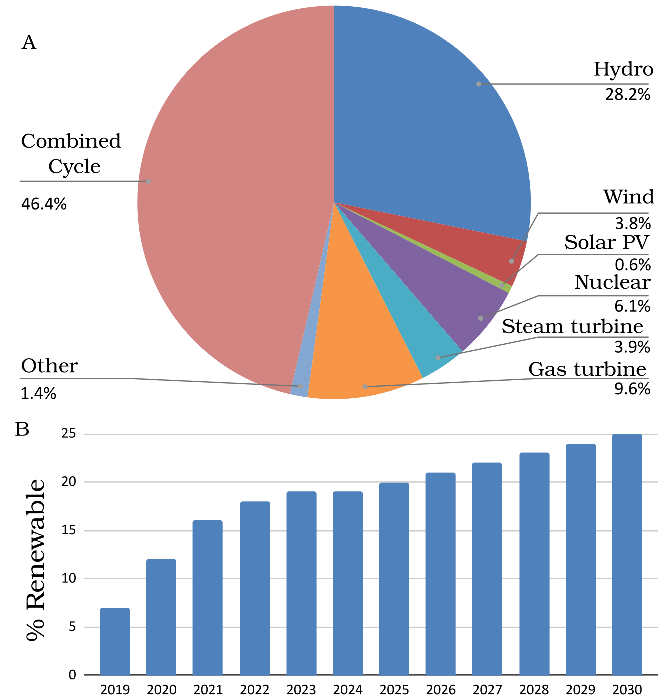

Fig. 2. A) Argentinian electricity mix B) Renewable scenario in the Argentinian electricity mix.

- Vehicle with diesel-powered internal combustion engine (DV).
- Fuel cell hybrid vehicle (FCHEV) powered with hydrogen.
- Battery electric vehicle (BEV) powered with electricity.
- Compressed natural gas vehicle (CNGV).

The WTW analysis is done from a public transport perspective by studying the powertrains in a bus for urban passenger transport. These powertrains are studied with two driving cycles designed to assess emission levels and fuel efficiency in the vehicles: Braunschweig as an urban cycle [29] and WHVC, which incorporates part urban and part on-road driving cycle [30]. Driving patterns significantly affect fuel consumption, and vehicle efficiency as shown in the analysis done by Ribau et al. [31]. For BEV and FCHEV buses, the impact of varying the range (100, 200, and 300 km) on the performance of the units was also studied.

2.1. Well to tank

This section details the mechanisms for the electric power generation, diesel production, CNG production and hydrogen generation in Argentina. For the GHG emissions an energy consumptions of the energy vector production and delivery the GREET 2019 model was used [9].

Electricity generation. As can be seen in Fig. 1, in the case of the electricity vector, the starting point is the mix of renewable, nuclear and fossil fuel technologies. Electricity is then transmitted through high voltage lines and distributed via medium and low voltage grids. Finally, the electricity is delivered to the bus through dedicated charging stations. Fig. 2A shows the mix of technologies, efficiencies and participation rates in electricity generation from Argentina's mix of primary energies for the 2019 scenario [32]. Fig. 2B shows the projected share of renewable in the electricity mix until 2030 according to the Argentine Ministry of Energy [28].

Each technology used for power generation from fossil sources has different feedstocks: in the case of the combined cycle, it has 88.42% of natural gas (NG) and 11. 58% of diesel; the simple cycle gas turbine has 91.18% of NG and 8.82% of diesel and, finally, the steam turbine has 16.06% of carbon, 59.1% of fuel oil and 24.84% of NG. A 14.65% of losses due to distribution and transmission in the grid is considered according to the latest available data from World Bank [33]. For the future scenarios (see Fig. 2B) it is assumed that the addition of new energy sources to the grid is done incrementally through renewable sources, maintaining the absolute amounts of electricity generated today, and without changing the efficiency or proportions of each primary energy source.

Diesel production. To model the diesel production routes, updated inputs from Argentina were taken and included, such as imported fuel transported by barge, conventional and unconventional crude oil from national reserves, crude oil transportation, refining, transportation and distribution of diesel (see Fig. 1). It also takes into account the blend with biodiesel as established by the regulation of the Secretary of Energy [34].

Compressed natural gas production. In order to build CNG production routes, up-to-date data for Argentina is taken, including conventional and non-conventional gas production and transportation through pipelines [35]. In addition, as shown in Fig. 1, natural gas compressor stations necessary for transportation and distribution were taken into account. The electric energy for this process is taken from the Argentinian electricity mix (see SubSection 2.1).

Hydrogen generation. Currently in Argentina, hydrogen is produced following the worldwide trend of steam reforming of hydrocarbons and hydrocarbon cracking. Since almost all production is captive, any additional hydrogen supply can be conceived outside the current energy mix. Given that Argentina does not currently have an infrastructure for the production, transportation, distribution and refueling of hydrogen for vehicles, the first scenario is one of business as usual and lower investment generating all the hydrogen through steam reforming using virtual pipelines. Another scenario is the production of green hydrogen (H_2) produced through water electrolysis with electricity from renewable sources, compressed and stored to be later transported and distributed by hydrogen pipelines. At the end of the WTT stage is the H_2 loading station, which is identical to that of the H_2 reforming route.

For future projections, the hydrogen production processes are maintained and their performance varies only due to the modification of the electricity generation mix. This is due to the incorporation of renewable sources in the electricity mix and their subsequent use during the production and, mostly, compression stages of hydrogen.

2.2. Tank to wheel

This SubSection provides a brief description of the components used in each of the passenger bus powertrains, and the different mathematical models used to perform the simulations. Fig. 3 graphically shows the speed frequency distribution of the two driving cycles used in this work. BEV and FCHEV powertrains were studied using models developed by the authors [11,10], while the diesel and CNG buses data was taken from the Söderena et al. report [27].

Table 1, shows the weights of all systems in all cycles, where the empty bus weight refers to the weight of the body excluding powertrain elements, the acronym FCS stands for the fuel cell system -which includes the hydrogen tanks-, and H_2 stands for the hydrogen mass consumed.

Diesel and compressed natural gas fueled buses. Both the DV and CNGV operate with a conventional power train and their weight is shown in Table 1. Further details can be found in Söderena et al. [27].

Battery electric bus. The parameters used for the battery model are shown in the A.1. For more details on the battery model, the reader is referred to Muñoz et al. [36].

Fuel cell bus. The FCHEV powertrain consists of a fuel cell system with a lithium-ion battery. The main source of power is hydrogen stored in a pressure vessel (350bar) that is converted to electricity in the fuel cell, with a lithium-ion battery (see SubSection 2.2) to supplement power at times when the Fuel Cell (FC) fails to generate the required power. This requirement may be due to delays in fuel cell response or to a power request that exceeds the maximum FC power. Battery charging through regenerative braking was also contemplated. The main characteristics of the FC stacks are shown in the Table A.2. For further information of the model used, the reader is referred to Correa et al. [11].

3. Results and discussion

In this section, the results of the well to wheel analysis as well as the total cost of ownership study are presented and discussed. Later the integrated index is presented combining the results of the energy consumption, the CO_2-eq emission index and the TCO followed by the projections of that index up to the year 2030. Finally an analysis of the energy saving and emissions abatement produced if the Argentinian urban buses fleet were to be converted to CNGVs, BEVs or FCHEVs is presented.

3.1. Energy consumption

The overall energy consumption is elaborated based on the amount of energy required per km traveled for the bus considering the WTW path.

The evolution of the technologies in the study period is not considered, i.e. the processes maintain the same efficiency for all scenarios.

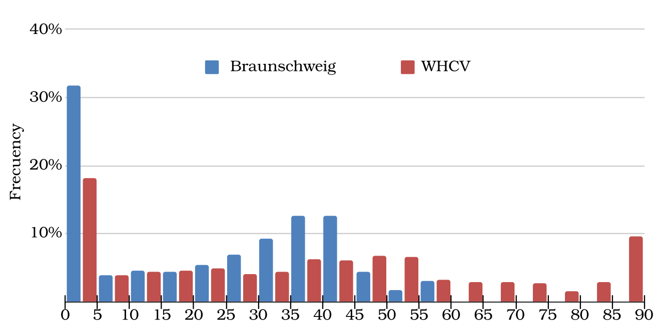

Fig. 3. Speed frequency of driving cycles.

Comparing between the Braunschweig and WHVC cycles for each technology, in Fig. 4, it is observed that the urban cycle has a higher energy demand than the harmonized cycle.

However, the difference within each bus technology presents some particularities: the proportion by which the energy consumption increases for a BEV when switching from the WHVC cycle to the Braunschweig cycle is 16.06% for a range of 100km, while for a range of 300km the proportion is 27%. This increase in the consumption ratio may be explained by the difference in vehicle weight. Comparing these values with those obtained for CNGV and DV (50.39% and 54%, respectively), is possible to see that internal combustion vehicles have a significantly higher energy consumption for urban cycles, due to the low efficiency of internal combustion engines in journeys with a high number of stops. For the fuel cell vehicles, this variation is 28.25% and 30.80% for the 100 and 300km ranges, respectively. This ratio is similar to that obtained for the BEV with the longest range, which suggests that the difference is mainly due to the energy consumption related to the acceleration and braking of the cycle.

It can be seen that the variation in range in FCHEVs has a lesser impact than in BEVs since the weight variation is smaller. In absolute terms of energy use, BEV technology provides the lowest energy consumptions and therefore the best energy efficiency indexes for all cycles, while for an urban cycle FCHEVs have a higher efficiency than CNGVs and DVs. On the other hand, for an urban-interurban cycle, the DV efficiency is higher than the one corresponding to FCHEVs.

Analyzing the energy consumption by stage, is possible to see that in internal combustion vehicles the consumption in the WTT stage is between 7% and 12.81% (CNGV and DV respectively) while for electric vehicles it is 52.84%, resulting to be the stage with the highest consumption. Fuel cell vehicles are located in an intermediate point, since their energy consumption in the WTT stage represents a 34.22%, when the FCHEV is fueled with green hydrogen. These variations are due to the different stages and transformations that the products go through to obtain the energy vector (electricity, CNG, diesel and hydrogen). In the case of electricity, the consumption due to the WTT step may decrease in the near future due to the increase in the percentage of renewables that make up the electricity mix. This variation would mainly affect BEVs, and to a lesser extent FCHEVs that consume electricity from the grid in pipeline transport processes.

3.2. Emission index

The environmental aspect of the analysis is captured by an index that takes into account the greenhouse warming potential produced by the gaseous emissions associated with each type of vehicle and its associated energy vector, throughout its life cycle [37]. The following considerations were taken into account when preparing the emission indexes for each type of vehicle:

- The technology-specific emissions rate Em_j is obtained from the emissions for each gaseous substance in the WTW analysis. Using the Intergovernmental Panel on Climate Change global warming potential factors [38], the index is expressed in units of kg of carbon dioxide equivalent (CO_2-eq) per km traveled.
- Nitrous oxide (N_2O) TTW emissions are added for diesel transport according to data provided by the European Environment Agency [39].
- The index is obtained normalizing the emissions rate according to

$$B_j = \frac{\min_{i=1,2,3} Em_i}{Em_j}$$

Fig. 5 shows the emissions and associated energy uses of the different energy vectors, for the production of 1MJ of energy. At this stage the

Table 1
Weight of all systems in all cycles, in kg.

Cycle	Range [km]	Vehicle bodywork	Pax	FCHEV			BEV		DV	CNG
				FCS	H_2	Total	BAT	Total	Total	Total
Braunschweig	100	11000	2700	1374.5	9.21	15472	1435.5	15260	15200	15700
	200			1775.4	19.07	15873	3195	16844		
	300			2139.8	29.42	16238	4950	18775		
WHVC	100			1301.6	7.2	15400	1237.5	15062.2		
	200			1611.4	14.85	15709	2524	16350		
	300			1921.2	22.5	16019	3960	17785		

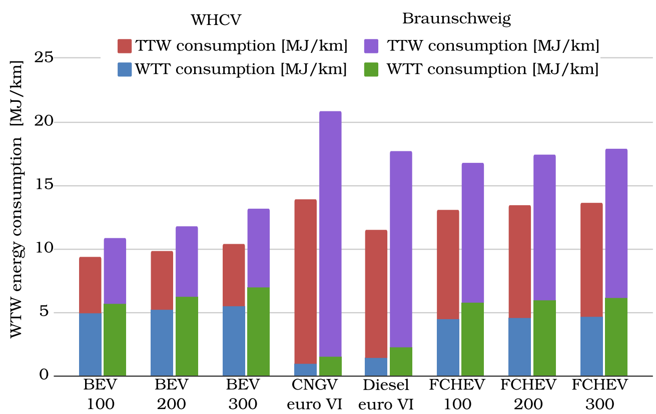

Fig. 4. Comparative WTW energy consumption between Braunschweig and WHVC cycles.

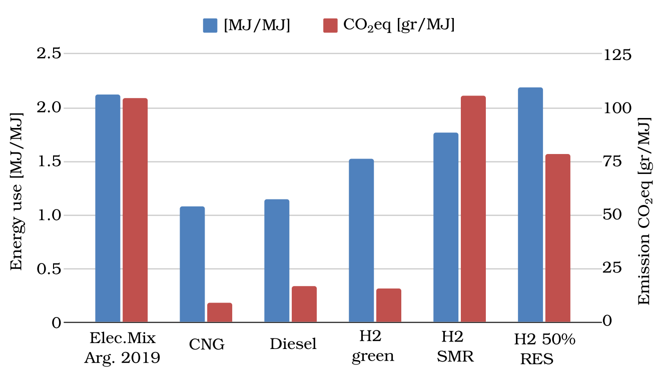

Fig. 5. Emissions and energy uses of the production of energy vectors.

CNG and diesel vectors have the lowest energy consumption for the production of the vector and the lowest emissions. Green hydrogen production has an efficiency close to 66% and similar emissions to diesel. The last two vectors shown in the figure correspond to H_2 production by natural gas reforming; and by electrolysis with energy from a combination of equal parts of electrical energy from the grid and electrical energy from non-polluting sources, e.g. wind power. The last two production pathways of H_2 are shown to compare them with the green H_2, and will not be used throughout this study since they have higher consumptions and emissions values.

Comparing the two cycles, for all technology options, a higher GHG emission is observed for the Braunschweig cycle than for the WHVC cycle. This result is linked to the higher energy consumption in the urban cycle, similar to what was observed in Fig. 4 and to what was analyzed in SubSection 3.1. The hydrogen vector used for comparison is green hydrogen, and therefore, its GHG emissions are due only to the compression process, which uses energy from the grid with the Argentinian electricity mix 2019. Analyzing the differences within the BEV category (Fig. 6), it is possible to see that GHG emissions depend on the vehicle's range. For both cycles in the FCHEVs, there are differences in emissions between the ranges studied, however these differences seem to be irrelevant. CNGV and DV emissions are the highest in both cycles, mainly due to TTW emissions, absent in all electric vehicles. Within the internal combustion engine (ICE) buses, in both cases CNGV GHG emissions are lower than those of DV.

Analyzing the WTT emissions, it can be seen that those corresponding to BEVs are the highest, due to the fact that energy comes from an electricity mix containing a high percentage of fossil fuels. GHG emissions in the generation and delivery of green hydrogen to the FCHEVs are the lowest, due to the fact that the main energy source is 100% renewable and zero emission. The generation of 100% renewable energy to power BEVs would imply a significant reduction in GHG emissions, but there could be difficulties related to energy transport in the electric grid (with a transport capacity that is currently close to the maximum allowed values [40]). The hydrogen production model used includes the transport step in pipelines (with its associated emissions due to the use of grid electricity for compression) from the generation sites to the charging site.

As analyzed in SubSection 3.1, for the period 2019–2030, no evolution in GHG emissions is considered for DV or CNGV. The variation of emissions is considered with the incorporation of renewable energy sources in Argentina's electricity mix, which affects BEV and FCHEV buses. It should be noted that through the Paris Agreement on Climate Change, the Argentinian government proposed a reduction of yearly total national GHG emissions from 368 to 359Mt of CO_2-eq until 2030 [41]. Electrification and hydrogen use in transport are among the proposed mechanisms for this reduction in emissions.

3.3. Total cost of ownership

Any development of new technologies requires an analysis of their commercial viability. Therefore, it is very important to compare the economic efficiency of different vehicle motorization technologies. This

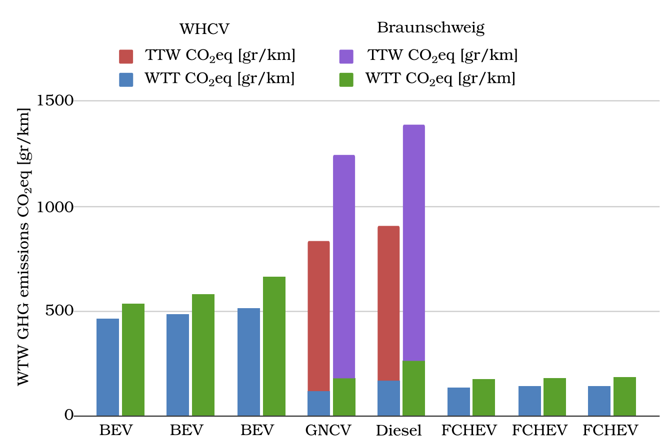

Fig. 6. Emissions of CO_2-eq for Braunschweig and WHVC cycles.

analysis is performed for buses with fuel cell technologies, and compares them with BEVs and ICE vehicles. The total cost of ownership model used examines FCHEVs in detail and was developed for the United States [42], although in this work it was modified to adjust to the parameters proposed by the World Bank for Buenos Aires [43] and other local data such as the Argentinian energy mix, the cost of electricity and the percentage of renewables. Thus, even if the reference values were those corresponding to Buenos Aires, the trends in future costs are consistent with the model proposed in the literature for the United States based on the current scenario in Argentina.

The only way to understand which components are responsible for current and future costs for vehicle construction and operation is to perform a detailed TCO analysis. This will provide a general framework of component costs, but more importantly, it will allow estimating future trends.

For the construction of the initial cost, the cost of each of the vehicle components was analyzed, including electric (or combustion) engine, fuel cells, hydrogen tanks, battery packs, electronics, as well as vehicle systems such as brakes, bodywork, suspension, etc. Operational considerations and their associated costs, such as fuel, maintenance, necessary infrastructure, etc., were also taken into account. The TCO model used does not take into account government subsidies and assumes a gross margin and a profit margin for the manufacturers based on the construction costs of the components. It is important to consider that, although many components are similar in all vehicles (such as chassis, seats, body, etc.), there are small differences that may require different construction molds, which can lead to differences in final prices. Given the huge number of different components that make up a vehicle, it is extremely difficult to determine which components are identical and which are similar but require modifications, implying price differences. This leads to different models having very different initial costs, which are expected to become more consistent due to economies of scale and technology maturation. The ICEV components are also considered to be already at a ”baseline” level due to overall economy of scale and technology maturity. Thus, TCO is strongly dependent on the current and future massification of a technology as well as its maturity. An important consideration of this model is the assumption that the FCHEV propulsion system components will reach full economy of scale within the next 10 years.

For this analysis, 12-meter buses were considered, with a fleet size of 100 units, traveling different daily distances, ranging from 100 to 300km. TCO is broken down into vehicle purchase cost and operating cost. For operation, the cost of fuel, charging station, maintenance, parts replacement cost (including battery pack and fuel cells) and insurance cost are included. In the model, it is originally assumed that the charging infrastructure costs are borne by the operator, however, in real scenarios, and particularly in the case of Argentina, this may not be true. It is also considered that BEVs require dedicated chargers as well as station chargers for opportunity charging during operation.

Current total cost of ownership. Fig. 7 shows the model case for the United States for ICEV, BEV and FCHEV TCOs, along with the estimated TCOs of BEV and ICEV for the Buenos Aires City metropolitan area [43].

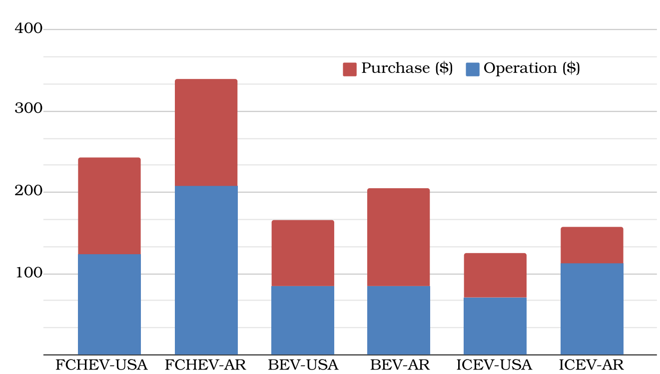

Fig. 7. TCO comparison for different locations and technologies. [43].

When ICEV, BEV and FCHEV are compared, the fact that FCHEV is currently the most expensive technology becomes evident. Cost estimates for the United States [42] have a lower value than those obtained for Buenos Aires [43], although it is necessary to consider that different models were used, which could easily explain the differences found. It is considered that the ICEV TCO, as a mature technology with widespread use, should be well established for the year 2019. It can be seen from the comparison in the TCO for BEV in the USA and Buenos Aires that the operating costs are very similar and the major cost difference comes from the acquisition of the technology.

To understand this difference, it is useful to consider the weight of each component in the final cost, both in the purchase of the vehicle and in the operation. In the case of vehicle purchase, and considering that an FCHEV shares many characteristics with ICEVs and particularly with BEVs, it is expected that the largest cost differences will come from the energy module. Currently, a fuel cell costs around 1500USD/kW [44], and when the hydrogen tanks are added, they make up almost 88% of the total cost of the power module and 15.6% of the total cost of the vehicle. However, when analyzing the variation in the cost of fuel cell systems, in recent years it is observed that between 2006 and 2018 there was a decrease in costs of approximately 60% [45]. Thus, like any emerging technology, it is expected that costs will continue to decrease rapidly until market scale and maturity of the technology is achieved. For these same reasons, and because batteries are now a widely commercialized technology, their cost is lower. Thus, if the trend in fuel cell cost reduction continues as expected, FCHEVs could reach an economically viable scale within the next 10 years, eliminating the additional cost of having an energy module running on hydrogen.

The cost of staffing the refueling stations is independent of the technology used. The capital cost of the drivetrain for battery-powered vehicles is highly dependent on the range, as the size of the batteries required increases proportionally with their increase and they constitute, for a range of 200km, the 21% of the total drivetrain [42]. Therefore, an increase in the required range generates a considerable increase in the capital cost of the vehicle. For example, for a vehicle with a range of 300 km, the capital cost is almost one percentage point higher than for a vehicle with a range of 100 km. This is due solely to the difference in battery size. In this type of vehicle, the fuel cost is calculated by multiplying the combined cost of electricity in dollars per kWh multiplied by the specific consumption (kWh per km). This specific consumption is an average considering urban and interurban cycles. The cost of electricity is calculated in relation to the cost of off-peak electricity and the cost of renewable electricity which is a weighted average based on the amount of renewables that are incrementally added to the grid. Finally, the rate applied to fuel is a fixed fraction of the cost of the fuel used [43].

In the case of FCHEVs the capital cost is also dependent on the range as this depends on the size of the hydrogen tank. However, this difference is not as important as in the case of BEVs and the variation in the capital cost between an FCHEV with $\leqslant$100 km and one with $\leqslant$300 km of range is only of $\leqslant$1 percent, since the tank cost constitutes a 15% of total drivetrain and the latter a 13% of total capital cost [42]. On the other hand, the duty cycle used has a much larger impact on vehicle specific consumption and therefore the change in duty cycle generates a cost difference between cycles close to 23%. In FCHEVs the fuel cost is calculated by considering the amount of hydrogen consumed per kilometer and the cost of hydrogen, considering production, transportation, storage, distribution and refueling. The vast majority of analyses suggest that all avenues for hydrogen distribution should decrease significantly in cost over the next decade [46–48].

On the other hand, electric motors (used in both BEVs and FCHEVs) have lower maintenance costs due to simpler mechanics, although the costs of replacing fuel cells and battery packs add an additional burden on the operator and must be done every 4 to 5 years. These costs are expected to reduce considerably as the technology matures, especially for fuel cells.

The other determinant of operational costs is the construction of the infrastructure required to operate FCHEVs and BEVs. For example, according to the model used by Ballard [42] a hydrogen refueling station for a fleet of 100 vehicles costs approximately 6–7 million US dollars. Similarly, infrastructure for BEV charging requires grid and electrical substation modifications, as well as opportunity charging stations. This makes infrastructure costs differ considerably depending on the operating model (opportunity or station charging). However, infrastructure costs can also be expected to decrease quite rapidly.

Fig. 8 shows the four vehicle configurations, except that BEVs were analyzed for the three ranges provided and FCHEVs for the two cycles studied. It can be seen that fuel cost is the main factor in the disaggregation of TCO for FCHEVs with respect to other technologies. For the case of the FCHEVs, the fuel cost calculation was performed using a benchmark price of 11.8USD/kgH_2, and 10 and 14USD/kgH_2 as the lower and upper bounds, respectively. In addition, a significant difference in the TCO of the two handling cycles studied can be seen for the FCHEV. The BEV for 200km of range is 33% higher than that of the diesel, while the FCHEV fueled with green H_2 for the on-road cycle, represents almost twice the TCO of the DV. On the other hand, CNGV is the vehicle with the lowest TCO and differs from DV in the costs of fuel and its associated taxes.

Future projections. Based on the cost structure presented above, it is possible to make cost projections for technology substitution. In this way, future TCO projections for the three technologies, FCHEV, BEV, and ICEV are obtained using the Deloitte-Ballard model for the USA for the next 10 years but using the current costs found for Argentina. Fig. 9 shows the projections for each of the technologies considered. For the BEV case the shaded area is shown for the range variation and in the case of FCHEV the shaded area represents the variation of H_2 refueling cost. Braunschweig and WHVC cycles were considered, and the obtained value is the average between both cycles. Thus, TCOs are expected to be highly dependent on the range considered, particularly in the case of BEVs where for ranges of 100km the breakpoint with respect to Diesel and CNG is in 2023 and 2025, respectively, while when a range of 300km is considered the breakpoints with respect to Diesel and CNG

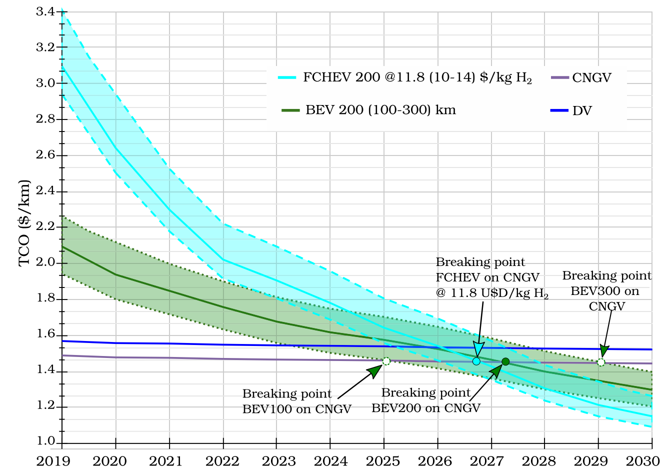

Fig. 9. Comparison of TCO projection for different technologies for the period 2019–2030.

appear in 2028 and 2029, respectively. Thus, the breakpoint for FCHEVs, with respect to diesel and CNG, occurs between 2026 and 2027 and is mainly dependent on the cost of hydrogen. According to the projection made in this work the cost could vary between 10 and 14USD/kg. According to the model, and considering a starting cost of hydrogen in 2019 of 11.8USD/kg [49], the TCO of FCHEVs is expected to be lower than that of BEVs around 2024 and 2028, for BEVs with a range of 300 and 100km, respectively, with a decrease in the TCO of FCHEVs of more than 50% in the next 10 years.

Thus, the most notable decrease in FCHEV costs is related to fuel cells and their replacement. The model forecasts a decrease in the price of fuel cells from 1500USD/kW in 2019 to 600USD/kW in 2029 [42]. This decrease in costs is mainly due to economies of scale and optimization of manufacturing methods, which are currently largely non-standardized. The life cycle of the systems is also expected to improve significantly. Currently, the life cycle of a fuel cell is approximately 25000 hours, but it is expected to reach 30000 hours by 2026 [42].

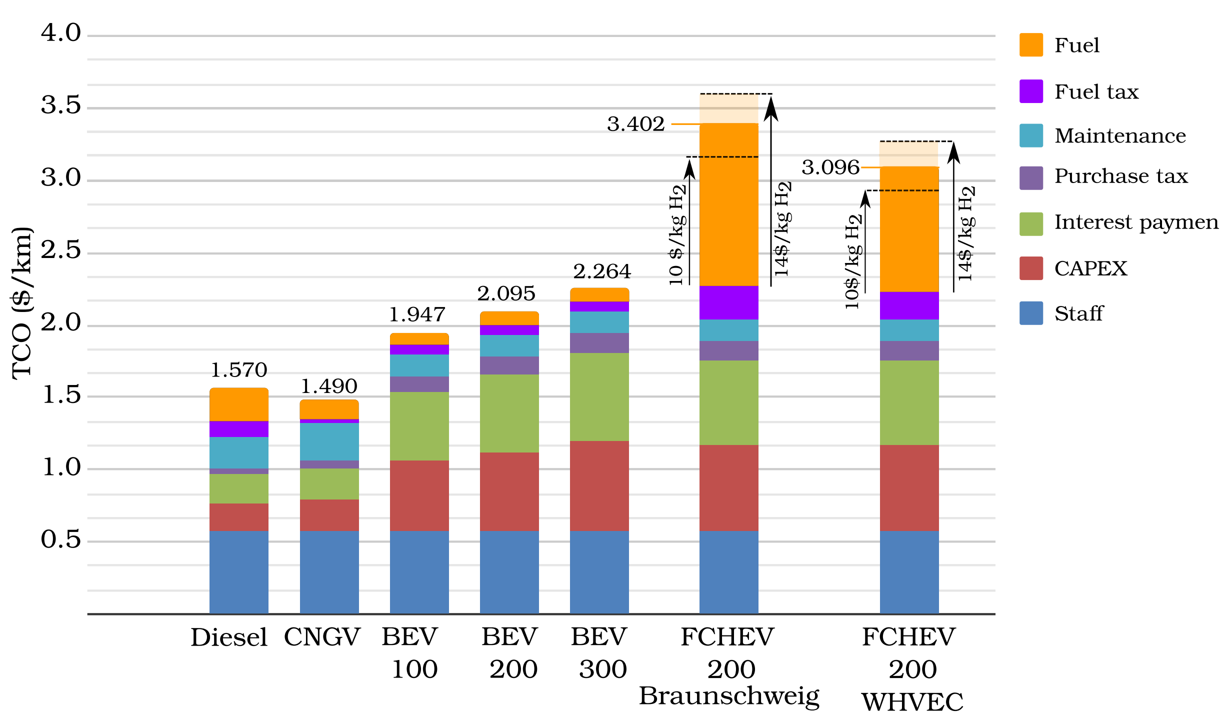

Fig. 8. TCO disaggregation for different bus technologies in 2019.

For this reason, the cost of fuel cells affects not only the initial purchase cost of the vehicle but also the operating cost, and the total maintenance cost is estimated to decrease by more than 60% over the next 10 years. On the other hand, hydrogen costs and infrastructure costs accounted for more than 50% of operational costs in 2019. Hydrogen has a higher cost than diesel and electricity used by pure electric buses. One of the reasons for this high cost is due to storage and transportation costs. With the scaling of these technologies, the price of hydrogen is expected to fall below half of the current price over the next 10 years [50]. It is important to note that these analyses do not take into account the intervention of the state both, with subsidies to support the introduction of new efficient and clean technologies and with measures to reduce the use of fossil fuel vehicles. These measures would significantly increase the purchase and operating costs of ICEVs by accelerating the arrival of the time when FCHEVs and BEVs become more cost-effective than ICEVs.

3.4. Index integration

By analyzing each index separately, it is possible to see how the different technologies offer the best result depending on the aspect being analyzed. In terms of energy efficiency, the most appropriate technological option is the BEV; while in terms of GHG emissions, FCHEVs have the best performance. Finally, in terms of cost, CNGV and DV internal combustion engine technologies are the most convenient at present. Seeking a univocal measure to evaluate bus performance that includes the indexes studied, a weighted sum of the normalized indexes is proposed. The first step consists of normalizing each index by dividing a reference value by the values obtained for the different technological options. For each aspect (energy efficiency, GHG emissions, and TCO) the reference value is taken as the lowest value (in absolute terms) obtained among all the options analyzed (powertrains, range, and cycle). In this way, normalized dimensionless values between 0 and 1 are obtained, where the selected option is more desirable the higher the value obtained. In other words, a higher cost index represents a lower economic cost. Likewise, the highest energy efficiency is given by the vehicle with the lowest energy use, while a higher environmental index represents lower GHG emissions.

The second step is to perform the weighted summation, weighting the indices by a value reflecting their relative importance.

The analysis for a Latin American country must take into account the difficulties in financing, which currently prevent the development of large-scale electrified means of transport in the region [43]. The factors of energy efficiency and greenhouse gas emissions appear as desirable characteristics, but secondary to the importance of investment cost. For this reason, to give the TCO factor a weight four times greater than that used for energy efficiency and GHG emissions it was decided, so that the weighting is done with the weights 4:1:1, respectively.

3.5. Comparative analysis of technologies trough 2019 to 2030

The operating cost factor was taken as the most important factor in the analysis. Previously, in Fig. 9 it was observed that in the year 2025 the cost of BEV100 falls below that of CNGV; while in the middle of the year 2026 the cost of a FCHEV is lower than that of CNGV.

By incorporating the energy efficiency and environmental factors, is possible to see that the overall picture for each technology changes noticeably. Fig. 10 shows the variation over the 2019–2030 period of the integrated indices for each technology option in the Braunschweig urban cycle.

For BEVs, vehicle range has an appreciable effect on both vehicle cost and vehicle energy efficiency and GHG emissions.

For FCHEVs, the variation in range produces a much less appreciable effect, however the cost of hydrogen significantly affects the result obtained. For this reason, the analysis was performed taking into account the cost of hydrogen as the most important variable.

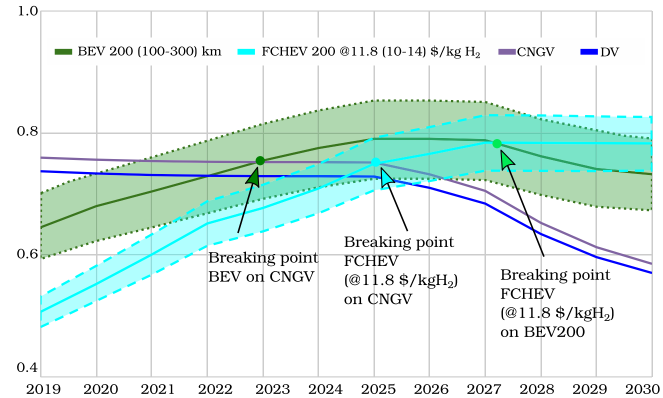

Fig. 10. Integrated Index for the Braunschweig cycle.

It is observed that for BEVs the integrated index shows increasing values for the first half of the period considered, surpassing both internal combustion engine options by 2023. BEVs show maximum values around 2024–2025, decreasing from 2027 onwards. The economic index explains a good part of this behavior, given that the decrease in TCO for BEVs is more noticeable in the first half of the period analyzed. Although it continues to decrease throughout the period, it is surpassed by the decrease in costs of FCHEVs around the middle of 2027. The variation in energy efficiency and environmental factors over the period explain the other part of the improvement in the integrated index for this technology. This improvement increases as renewable energy sources are incorporated into the grid, varying its share in the electricity mix from 6.1% in 2019 to 25% in 2030.

In the case of FCHEVs, the improvement in the indices is even more dramatic, surpassing in 2025 the integrated index for DV and CNGVs and increasing to surpass BEV values during 2027. The reduction in TCO again explains most of this behavior, due to the noticeable decrease in costs as the technology matures and because of economies of scale. The inclusion of environmental and energy efficiency factors, which improve with the inclusion of renewable sources, explain the rest of the behavior. Since by the end of the period analyzed the TCO of FCHEVs is the lowest of all the considered options, it is observed that their integrated index presents the highest values towards the end of 2029–2030.

Fig. 11 shows the variation of the integrated index over the 2019–2030 period for the WHVC cycle. In this case, the differences between the three technologies become more noticeable. The trend is similar to that observed in the Braunschweig cycle, but unlike the previous case the energy efficiency for FCHEVs is notoriously higher than that of CNGVs and DVs (see SubSection 3.1) and the emissions associated with FCHEVs are even lower than those of BEVs, as analyzed in SubSection 3.2. For this reason, the integrated index for FCHEVs increases rapidly until it surpasses both CNGVs and DVs as well as BEVs in

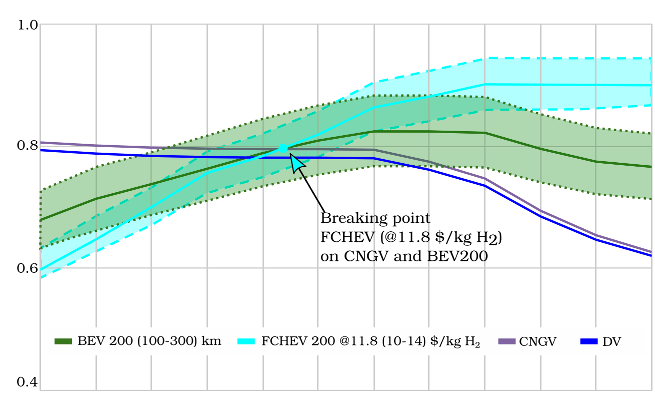

Fig. 11. Integrated Index for the WHVC cycle.

2023, presenting an appreciable difference in the index above BEVs from the second half of the period analyzed.

The BEVs increase in their integrated index in the first half of the period analyzed, reaching their maximum value around 2025 and then decreasing as they are surpassed by the values of the FCHEVs in the second half of the period.

3.6. Argentinian urban bus fleet analysis

In 2019, the transportation sector accounted for 33% of the country's energy demand, with total annual emissions of 50.18Mt of CO_2-eq corresponding to 26.6% of the country's total emissions from the energy production and consumption [1]. The significant participation of the transportation sector in the energy demand is explained by the continental extension of the Argentine Republic, which entails an important demand for long distance transportation, both for passengers and cargo. The road network consists of approximately 40 thousand km of national roads, which constitute the primary trunk network, 189 thousand km of provincial routes and approximately 285 thousand km of roads administered by the municipalities, making up the tertiary road network. The Argentine vehicle fleet is 14 million vehicles, of which 10.6 million are cars, 2.6 million are light utility vehicles, 678000 are cargo trucks and 84000 are buses for passenger transportation. The consumption for transportation was supplied in 2019 with a 39% of diesel oil, a 36% of gasoline, a 12% of natural gas, a 9% of biofuels and a 4% of other fuels. Within the buses for passenger transportation, 28000 units operate in urban contexts. The rest of the units operate interurban and long distance.

According to Calabrese et al. [51] the total emission of urban passenger buses in Argentina for the year 2017 was 1.55Mt of CO_2-eq. It should be clarified that urban buses are Euro IV and V and each unit travels an annual average of 42000km [52]. To calculate the energy and environmental effect of converting the urban bus fleet to electric propulsion, whether battery or fuel cell, the current urban bus fleet is analyzed, using the number of km traveled per bus in a year and the indexes calculated in SubSections 3.1 and 3.2 the total amounts of energy needed to power the bus fleet with electricity or hydrogen are obtained, as well as the abatement of CO_2-eq produced by switching the fleet from fossil fuel to less polluting vectors. Tables A.3 and A.4 show the annual consumption and emissions for both cycles, calculated on the entire fleet of urban buses in Argentina for 2019 and 2030, respectively. As can be seen in Table A.3, CNGV has higher energy consumption for both cycles, 18.20% in the urban cycle and 21.04% in the intercity cycle with respect to DV. However, CNGVs could reduce 10.07% in CO_2 emissions. This result is consistent with [53], who indicated that hybrid trucks based on compressed natural gas have 9.1% −18.7% less CO_2-eq emissions than those that run on diesel. Likewise, it is possible to see that if the entire fleet of urban buses is converted from DV to BEV, energy consumption would be reduced by between 25 and 38% (depending on the autonomy sought) and GHG emissions by between 52 and 61%. This consumption represents an energy saving of 2077GWh and an abatement of around 0.93Mt of CO_2-eq per year for buses with a range of 100km. In the last year (2020), photovoltaic generation in Argentina was 1344GWh and energy generation through Biomass and biogas was 725GWh, which, added together, are equivalent to the energy savings produced by the transformation of the entire fleet of diesel buses to electric buses with batteries. For FCHEVs, energy consumption is very similar to that calculated for DVs, but if the entire bus fleet in Argentina is converted to hydrogen-powered fuel cell buses, nearly 1.3Mt of CO_2-eq emissions could be reduced, which represents a 87% reduction in GHG emissions. To generate the annual green hydrogen needed to power the bus fleet through wind energy (based on urban cycle consumption), using electrolyzers with an efficiency of 52.4kWh per kg H_2 and a capacity factor of 54.9% [54], a dedicated capacity of 1.13GW would be required, which is comparable to the wind power installed during 2020 in Argentina, which was 1.01GW.

For the year 2030 (see Table A.4), the emissions and energy consumptions of DVs and CNGVs are identical to those calculated for 2019. Only BEVs and to a lesser extent FCHEVs change substantially. This is due to the fact that the penetration of renewable energy has a strong impact on the reduction of emissions and consumption in electricity generation. In the case of the vector H_2, the change is related to the (grid) energy source used for the compression of the vector. These results increase energy savings and deepen the reduction of GHG emissions, produced by the transition from DV to BEV.

4. Conclusions

In this work a general method was developed to compare the energy, environmental and economic performances of different types of buses associated to their energy vectors, using a single multiphysics index. From the developed method and analyzing the results is possible to conclude that:

CNGV is today presented as a better means of passenger transport, both for urban and intercity uses, than the diesel vehicle. As shown in Section 3, this result is evident from the integrated index, as well as in terms of both equivalent CO_2 emissions and TCO. For urban cycles, BEVs show the maximum values for the integrated index between the years 2023–2025, decreasing from 2027 onwards. Due to the fact that the index for BEVs is shown to be highly sensitive to vehicle range, from 2022 onwards the BEV with a range of 200 km outperforms the CNG bus. On the other hand, if ranges of 300 km are required, the break point is further away (2026). Hydrogen fuel cell buses projection show an increase in all the indexes, exceeding the integrated index for DV and CNGV in 2025 and continue to increase to exceed the BEV values during 2027. For intercity cycles, BEVs have lower comparative advantages than in urban use. The tipping point between technologies using internal combustion engines and those using emission-free electric motors is between 2023 and 2024. However, the break point with CNGVs occurs simultaneously with FCHEVs. From that point on, hydrogen-powered buses are much more efficient from the point of view of the integrated index. It is viable to affirm that, based on the analysis carried out on this work, the transition of the entire fleet of urban buses in Argentina towards zero emission technologies is predicted to be beneficial from the points of view of the energy consumption, environmental emissions and of the economy. The emissions abated and the amount of energy saved by this transition are significant in absolute terms. To conclude, this method can be used for the study of other scenarios and countries and the data presented can be used by decision makers to guide the efforts during the transitions towards zero emission technologies.

CRediT authorship contribution statement

Pedro Muñoz: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Esteban A. Franceschini:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **David Levitan:** Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **C. Ramiro Rodriguez:** Investigation, Writing – original draft, Writing – review & editing. **Teresita Humana:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Gabriel Correa Perelmuter:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.enconman.2022.115412.

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