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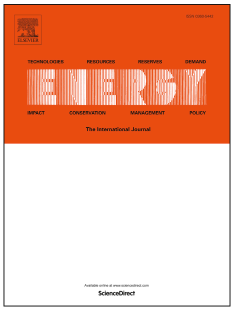

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A comparative energy and environmental analysis of a diesel, hybrid, hydrogen and electric urban bus

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Abstract

In this work, a comparative analysis of energy and environmental performances, on four types of urban passenger buses powertrains was carried out within the well-to-wheel scope in Argentina, Chile and Brazil. The powertrains studied were: internal combustion engine fed with diesel, fuel cell hybrid electric vehicle fed with hydrogen, battery electric vehicle fed with electricity and hybrid electric vehicle fed with diesel. The aim of the study is to understand what the influence of the energy pathway, the electricity mix, the driving conditions and different ranges is, in the current and future deployment of urban passenger vehicles. We found that the electric vehicles are markedly superior in the tank to wheel step, nevertheless actions to improve their energy and environmental performance should focus on how to generate clean energy within the electricity mix and with what technologies. For the fuel cell powered buses to be competitive, the production share of hydrogen from wind or other zero emission technologies should be more than 50%. In Argentina and Chile, the buses with internal combustion engines are still an important alternative in the current scenario only for long ranges, instead Brazil turns out to be ideal the application of full electric buses.

Keywords: Well-to-wheel, Emissions, Energy efficiency, Hydrogen, Battery, Buses

Abbreviations and acronyms

AC	Alternate current
ADS	Average driving speed
AER	All electric range
BAT	Battery
BEV	Battery electric vehicle
CO	Carbon monoxide
CT	Charging time
DC	Direct current
DOD	Depth of discharge
DOE	Department of energy
DV	Diesel vehicle
Eff.	Efficiency
EI	Emission index
EM	Electric motor
EV	Electric vehicle
FC	Fuel cell

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FCHEV	Fuel cell hybrid electric vehicle
FCS	Fuel cell system
FE	Fuel economy
GHG	Green house gases
H_2	Compressed gaseous hydrogen
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
ISI	Integrated sustainability index
LCA	Life cycle analysis
LIB	Lithium-ion battery
NOx	Nitrogen oxides
PEMFC	Proton exchange membrane fuel cell
PKE	Positive kinetic energy
PHEV	Plug-in hybrid electric vehicle
RES	Renewable Energy Sources
RPM	Revolutions per minute
SoD	State of discharge
TEE	Total energy efficiency
TTW	Tank to wheel
VGE	Vehicle gravimetric energy density
WTT	Well to tank
WTW	Well to wheel
ZEV	Zero emission vehicles

1. Introduction

Is well known that, in urban areas, car travel contributes a significant amount of the overall carbon footprint and that, in general, public transport is a more ecological way of traveling. Even when public transport is usually cleaner and cheaper than driving a car, there are cumbersome elements to account in the selection, especially in big cities in the South American countries where this study is developed. Due to the high acquisition cost of zero emission vehicles in contrast to the lower costs of ICE vehicles, market penetration of the BEV and FCHEV becomes much slower. In South America this situation is much more accentuated, therefore the introduction of electric vehicles is really very low. In 2018, Chile and Brazil vehicles stock was 250 BEVs and 680 PHEVs, over a global stock of 3 million, which represents less than 0.03%. The definition of local or national governments in the regional context to produce public policies that could generate changes in mass transport systems should have a global perspective that allows to assess the situation taking into account environmental, energy and operational aspects. In the public transport sector, it is very probable that a new technology 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 [1]. Following this argument it is necessary to discuss the hydrogen and electric recharging infrastructure, to see if FCHEV and BEV may prove to be a key long-term technology in the transition to a more sustainable transportation system. In the case of hydrogen stations, taking into account that natural gas steam reforming produces GHG, using renewable hydrogen from water electrolysis in situ is a green alternative for the future [2–4]. The hydrogen stations could be installed in the same point as fossil fuels ones, avoiding piping for its transport. Nevertheless, Yoo et al. [5] shows that for the Korea case, the amount of electricity required to drive the FCHEV by 1 km using the H_2 produced with electrolysis at the on-site gas station is 3.5 times the amount of electricity required to drive the EV by 1 km. For the charging stations deployment for the adoption of electric buses, considering that the energy can be supplied by electricity companies at charging stations, these should be located in strategic places in each city [6]. In specific literature there are numerous works that evaluate the environmental performance of alternative buses through the use of WTW analysis [7–10]. Several articles present environmental impact assessments of different configurations of vehicles, focusing on ZEV penetration, using LCA as study methodology [11–13]. The results shown in Xylia et al. [14] highlight that, although higher battery capacities could help to reduce emissions associated with fuel consumption of urban buses, this does not necessarily lead to a reduction of the total emissions. In some works, the impact of generation and the energy pathway is analyzed by conducting comparative evaluations of electric vehicles using LCA in different regional contexts [15–17]. Most of them show that EVs can be more sustainable and more efficient in the sense that the environment is maintained. In the South American context, Choma and Ugaya [18] work, proposes to identify in the Brazilian context, the environmental impacts of BEVs. In this work, a comparative analysis of the impact of the energy mix evolution, the range and the driving cycle on: DV, HEV, FCHEV and BEV urban buses for Argentina, Brazil and Chile using Energy and environmental performances, is made using the novel method proposed in the authors' previous work [19]. Unlike many published works, in this paper the comparative analysis of energy usage and environmental sustainability is conducted using a unique index that includes efficiency ratios, operational aspect and the environmental impact. This index makes the understanding of this complex analysis more accessible for non experts considerations.

2. Method and description of case study

The method used to assess the performance is the Well-to-Wheel analysis which comprehends the energy consumptions and emissions from the extraction of the raw materials to the buses operation. As it can be seen in Figure 1, the analysis is divided in two parts, WTT and TTW. The WTT analysis is carried out for the generation of the three energy vectors needed, diesel, hydrogen and electricity, and comprises the transformation from raw materials to energy vectors and their distribution. This analysis is done for the current situation (2017) of each country and also for a future scenario (2030).

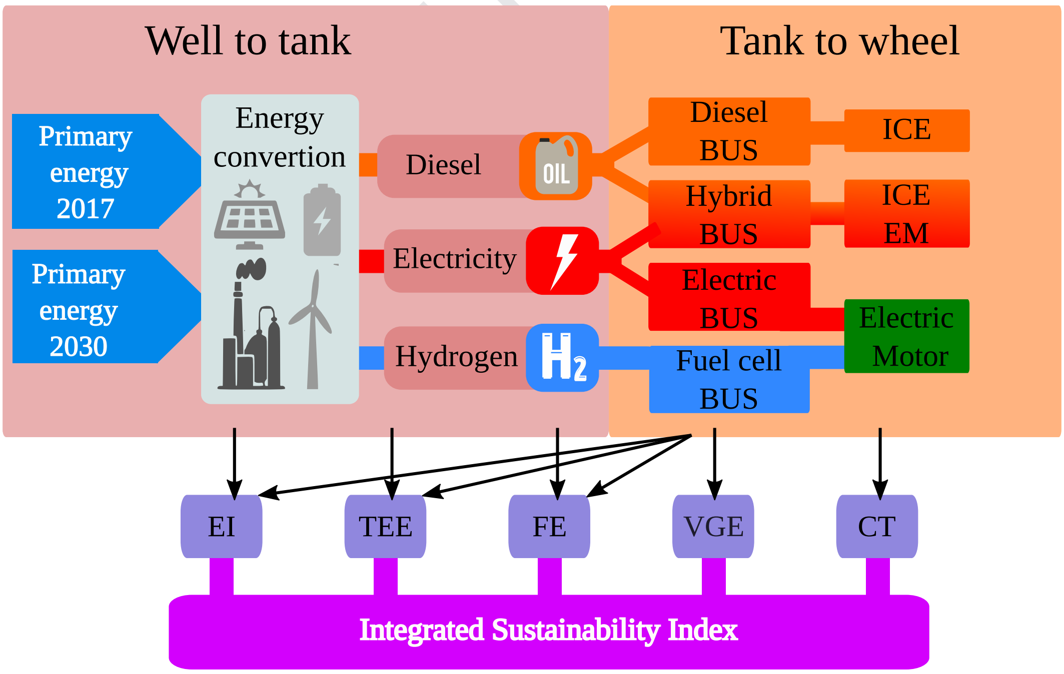

Figure 1: WTW analysis diagram

For each country electricity mix, all available generation methods were taken into account in their proper share, considering the losses due to the transmission and distribution of energy. For the biodiesel produced from soybeans and tallow, and diesel from crude oil, the energy usage and the emissions for its production and distribution were considered. For the hydrogen generation, natural gas steam reforming is proposed for the current scenario and a mix with wind power electrolysis is proposed for the future. The WTT emissions and consumptions were calculated using Argonne's GREET model [20].

The TTW analysis evaluates the performance of the buses in two different driving cycles, considering four different ranges, 100 km, 200 km, 300 km and 400 km. The WTW performance in those steps is evaluated trough normalized indexes an then an integrated index is proposed to evaluate all the aspects of the powertrain.

2.1. *WTW analysis*

In the well to wheel analysis, the results obtained from the WTT and TTW are combined, adding the consumptions and emissions given in each step. To study the performance of the buses, five relevant indexes are chosen. The indexes were computed studying the fuel used and the emission produced in the TTW step and then, the energy, fuels and emissions of the WTT step are computed for the fuel utilization in the TTW step and added. The proposed indexes are: Total energy efficiency (TEE), Fuel economy (FE), Emission index (EI), Charging time (CT) and Vehicle gravimetric energy (VGE).

2.1.1. *Efficiency indicator*

As efficiency indicators the TEE, the FE and the VGE indexes were considered. The TEE index measures how good the energy conversions were along the pathway. The WTW efficiency is calculated as the ratio of energy solely needed to move the bus and the actual energy of the fuels and the energy needed to produce them. The FE measures the traveled distance over the total energy consumed. Not only it measures how efficient is the energy conversion but also takes into account the purpose of the system, which is to cover the greatest possible distance with the lower energy expenditure. The VGE is used to measure the efficiency of the powertrain technology to store energy. The energy of the diesel and the stored hydrogen is calculated considering their lower heating value.

2.1.2. *Environmental indicator*

As a part of the environmental aspect of this study, another important aspect of the buses performance is the pollutant gaseous emissions generated. Within this indicator a single index, named emission index, was used. In this work only two air contaminants (NOx and CO) were considered and the evaluation is done according to Correa et. al. [19].

2.1.3. *Operation indicator*

The different systems will also be measured according to the charging time of the units per km. Along with the high costs of the electric powertrains due to the FCS and batteries, the charging time is one of the obstacles for the adoption of this technologies in the near future. The FCHEVs are less affected since the refuelling rates ranging from 0.9 kg/min [21] to 5 kg/min [22]. In this work the upper limit of 5 kg/min was adopted, following the experience of BC Transit in Whistler, Canada [22].

On the other hand, BEVs have different alternatives for battery charging such as opportunity charge, end station or overnight charge [23]. The selection of the charging system depends on numerous factors such as length of routes, shift duration, bus fleet size, service frequency, circulation length, average operating speed, operation hours, etc. [23, 24]. Opportunity charge offers the possibility of charging the battery during the boarding or disembarking of passengers using fast charging that enables to charge the batteries up to 66% in 10 min [25] with a low degradation rate and could operate seamlessly for 24 hours [26]. Opportunity charge also offers the possibility of downsizing the batteries[23] lowering the cost of the buses, although this system requires several charging spots being installed along the route, rising the overall cost of the systems [26]. End station charges refers to the charge at the end of the bus trip, and an overnight charge is when the bus recharges only one time a day. In this work we assume a conservative approach and select an overnight charging, with a slow charge to preserve the battery. Independently of the battery size, the charging time remains constant leading to a 6 hour charge for the BEV. Due to the large hydropower share in the electricity mixes of the studied countries, the overnight charge might reduce the environmental impacts [27]. This type of load could also be more advantageous in terms of electricity prices, since it occurs mainly in non-peak hours.

For the diesel delivery to the DV and the HEV a 70 liter per minute flow was adopted.

Two minutes were added to every charging time to account for the handling time during the refueling operation of all the powertrains.

The Charging time index is used as the only operation indicator and it is expressed in minutes per km allowing us to compare different ranges for the same powertrains.

2.2. WTT assumptions

Each country analyzed is shown in Figures 2, 3 and 4, with the current scenario in the inner circle and the future scenario in the outer circle. In all scenarios, the losses due to electricity transmission and distribution were taken into account using the data from the world bank data page [28], where the electric power losses in transmission and distribution are 14,33% for Argentina, 15,77% for Brazil and 6,33% for Chile.

2.3. Argentina WTT

2.3.1. Electricity mix

For the current electricity mix, the monthly report from the electricity wholesale market administrator company (CAMMESA by its Spanish acronym) [29] was used to calculate the average share of each generation technology over the year 2017. The future scenario was defined using the work of Di Sbroiavacca et al. [30]

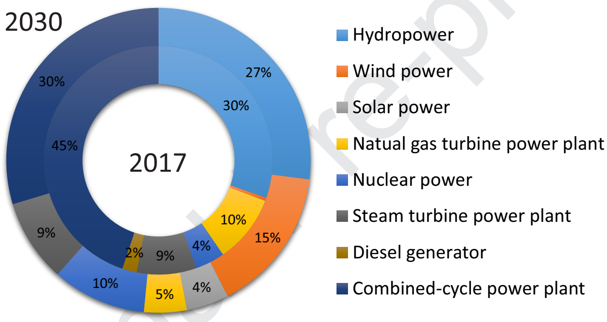

Figure 2: Electricity mix Argentina

2.3.2. Diesel production and distribution

The diesel production was computed as a blend of 90% diesel and 10% biodiesel from soybeans, as the resolution 1125/2013 of the Argentinian Secretary of Energy establishes [31]. Biodiesel is proposed as a way to diversify the energy sources without the need of a new infrastructure or modification in the vehicles and as a renewable fuel [32, 33]. In view of the sustained increase in the percentage of biodiesel in the mixture, in the future scenario a 20% of biodiesel blend from soybeans is proposed.

2.3.3. Hydrogen production and distribution

For this study, in the present scenario for all the countries studied, the hydrogen is obtained from natural gas steam reforming, and distributed via a virtual pipeline i.e. the gas is loaded in tanks and distributed to the refueling stations in trucks. In the future scenario for all the countries studied, a mix source is proposed 50% of the H_2 obtained from natural gas reforming, and 50% trough wind powered electrolysis of water. The H_2 is, again, distributed via a virtual pipeline.

2.4. Brazil WTT

2.4.1. Electricity mix

Due to the diversity of available resources, Brazil has different types of power plants, with hydropower being the predominant one, as shown in Figure 3. The electricity mix was modeled using data published by the Ministry of Mines and Energy [34], and the future scenario was drawn from Sanchez Moore et al. [35]. In the future scenario, wind energy seems to be the prioritized source to complement the use of hydropower [36].

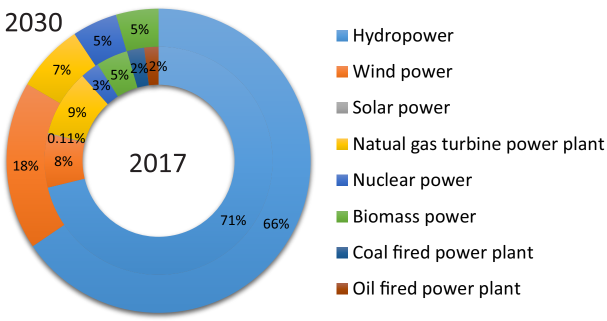

Figure 3: Electricity mix Brazil

2.4.2. Diesel production and distribution

By Brazilian law 13.263 [37] the presently marketed diesel is a blend with 9% of biodiesel, which is mainly produced from soybeans and tallow [38]. Again, in the future scenario a blend with 20% of biodiesel is proposed.

2.4.3. Hydrogen production and distribution

As in the case of Argentina, in Brazil almost all production (920 000 t per year) is captive and it is consumed mainly by oil refineries and fertilizer industries. According to Hotza and Costa [39] Brazil has capacity for obtaining hydrogen, because the diversity of raw materials for renewable energy generation. The same scenarios of Argentina are proposed for Brazil hydrogen production.

2.5. Chile WTT

2.5.1. Electricity mix

The electricity mix studied (see Figure 4) corresponds to the Central Interconnected Sector (SIC in Spanish acronyms), which represents 78% of the total electric generation capacity and was developed using the data from the "Open Energy initiative" web site from the National Commission of Energy [40]. In Chile, more than 70% of its basic energy sources are imported [41] because the country has no significant oil, gas, or coal resources, so the only domestic alternative is hydropower and other renewable energy sources [42]. The future scenario (Figure 4) was conceived considering the work of Gomez et. al. [41]. This scenario was modeled using a combination between the market and non-conventional renewable energy policy scenarios proposed by the authors.

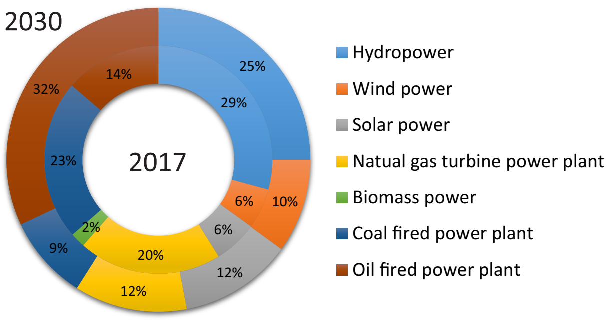

Figure 4: Electricity mix Chile

2.5.2. Diesel production and distribution

Even though there is a law in the country that allows a blend of biodiesel within 2% and 5%, it is not compulsory [43]. In light of that, in the present and future scenarios the GREET model for diesel from Chile was considered, without any biodiesel blending.

2.5.3. Hydrogen production and distribution

Chile has an increasingly lower renewable costs, with electricity costs around $30/MWh, which could also be competitive for the renewable-based hydrogen production [44]. The same scenarios of Argentina are proposed for Chile hydrogen production.

2.6. TTW assumptions

The TTW analysis covers the performance of four buses with different powertrains: ICE fed with diesel, HEV in parallel fed with diesel, FCHEV fed with hydrogen and a BEV fed with electricity. The simulation parameters of the urban passenger buses and their values are listed on table 1 and were taken from the ADVISOR software[45].

Table 1: Bus parameters

Parameter	Value	Unit
Bodywork weight	12636	kg
Aerodynamic drag coefficient (C_D)	0.79	-
Bus frontal area (A)	7.24	m^3
Rolling factor (f_0)	0.0094	-
Wheel radius	0.486	m
Passengers weight	1500	kg

The dynamic model of the vehicle takes into account the grading resistance (1), aerodynamic drag (2), rolling resistance (3) and the acceleration forces (4). In this study, the assumed slope is zero ($\alpha = 0$), therefore the term referring to the grading resistance is equal to zero in the equation (1).

$$F_g = Mg\sin(\alpha) \tag{1}$$

$$F_d = \frac{1}{2}C_D A\rho V^2 \tag{2}$$

$$F_r = \frac{T_r}{r_d} = (f_0)\, Mg\cos(\alpha) \tag{3}$$

$$\sum F = M\frac{dV}{dt} = F_{wheel} - F_g - F_d - F_r \tag{4}$$

Where F_g is the grading resistance, M is the vehicle total mass, g is the gravitational acceleration, F_d is the aerodynamic dragging force, C_D is the drag coefficient, A is the frontal area of the vehicle, V is the instantaneous speed, F_r is the rolling resistance force, T_r is the rolling resistance torque, r_d is the wheel radius, f_0 is the rolling resistance coefficient and F_{wheel} is the force applied by the vehicle powertrain.

The computational models allows to extract the consumption and emissions of the buses. The DV and HEV were simulated using ADVISOR [45] and the FCHEV and BEV were simulated using models developed by the authors[46, 47]. The FCHEV and BEV are zero emission vehicles (ZEVs), meaning they do not produce contaminant emissions during their operation. This vehicles are propelled by electric motors powered with electricity from batteries, FCS, both, or any other electricity source; having a higher overall efficiency and a lower energy consumption when the vehicle is idle while the ICE needs fuel to keep the engine running. In addition to the zero emissions, the BEV and FCHEV, along with the HEV, have the advantage of having regenerative brakes, which allows to recover and store energy that would, otherwise, be lost as heat.

2.6.1. Bus system energy analysis

To represent the behavior of the energy flow in the powertrain, Sankey diagrams were used. This diagrams are commonly used to represent the flow of energy in hybrid systems and to identify possible ways to improve the efficiency [48–50]. Therefore, in each of the buses studied, the energy consumption and the losses will be studied, as well as the possible energy recovery through regenerative braking. In any case, the diagrams are indicative, since for each cycle (Uk & EUDC) and each range (100 km, 200 km, 300 km & 400 km), a different Sankey diagram would be needed.

2.6.2. DV and HEV Buses models description

For the HEV bus a parallel powertrain configuration was adopted. The table 2 shows the system components and weights of the DV and HEV, the values were taken from the ADVISOR software[45]. The weight of the fuel is not considered in this study and thus the net weight is invariant.

In Figure 5 the energy distribution diagram for the ICEV system can be seen, which is the simplest system of the four studied. The energy balance for the ICEV and HEV is represented in the equations 5 and 6, with their associated losses.

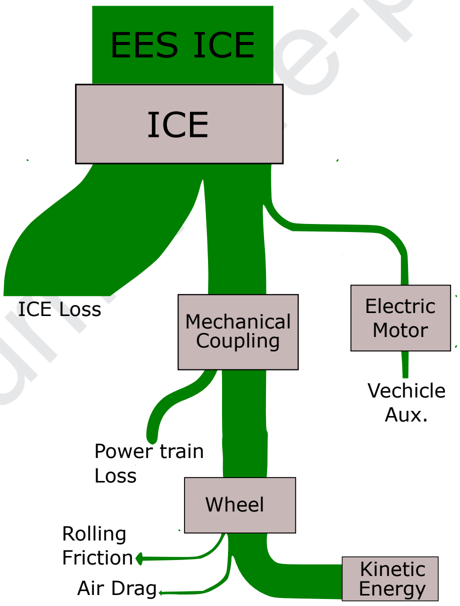

Figure 5: Schematic Sankey for the ICEV

$$ESS_{ICE} = EW + Mloss + ICEloss + Veh.Aux \tag{5}$$

where ESS_{ICE} is the ICE Energy Storage Systems, EW is the wheels energy, $Mech_{loss}$ is the mechanical loss that entails the losses of the differential and final drive and $Veh.Aux$ is the vehicles auxiliaries energy.

In Figure 6 the charging energy from the braking systems, the discharging energy, the losses, and the ICE net energy during the vehicle usage can be seen.

$$ESS_{HEV} = EW + PT_{loss} + Veh.Aux - ERB_{net} - B_{loss.out} \tag{6}$$

where ESS_{HEV} is the HEV Energy Storage Systems, ERB_{net} is the energy recovered in the battery through regenerative braking and B_{loss_out} is the energy loss in the charging process. Furthermore, PT_{loss}

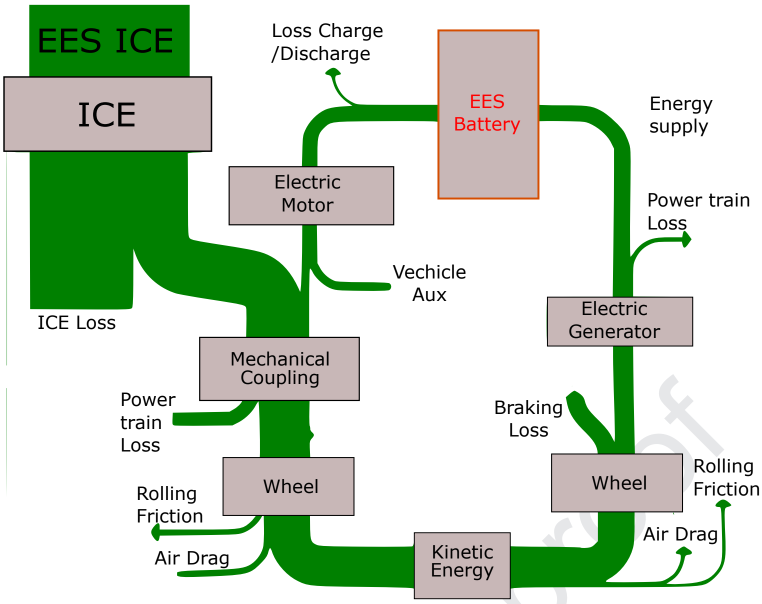

Figure 6: Schematic Sankey HEV

(eq. (7)) are the powertrain losses which includes: $Mech_{loss}$, EM_{loss} the electric motor loss and $Elect_{loss}$ the electronic losses (DC/DC, DC/AC and controllers).

$$PT_{loss} = \sum(Mech_{loss} + EM_{loss} + El_{loss}) \tag{7}$$

Table 2: System and Weights of the DV and HEV

Vehicle	Electric Propulsion	Powertrain weight	Gross weight
Diesel	No	1262 kg	15389 kg
HEV	LIB: 300 cells of 6Ah 100 kW electric motor	895 kg	15031 kg

2.6.3. BEV and FCHEV Buses models description

The FCHEV consists of 350 bar hydrogen tanks, a 150 kW FC stack, marketed for electric buses, with its balance-of-plant and a LIB meant to aid in the moments of high demand when the FCS cannot meet the requested power, due to the FCS inertial delay or because the requested power exceeds the FC maximum power. The PEMFC stack dynamic model was extracted from the work of Correa et al. [51, 52]. The battery can be charged during operation with the FC power surplus or through regenerative braking. The total vehicle weight of powertrain of FCHEV is:

$$W_{PT} = W_{FC} + W_{BAT} + W_{TH_2} + W_{EM} \tag{8}$$

Where W_{PT} is the powertrain weight, W_{FC} is the FCS weight, W_{BAT} is the battery weight, W_{TH_2} is the hydrogen storage system weight and W_{EM} is the electric motor weight.

The weight of the FCS and the hydrogen storage systems are obtained with the following equations:

$$W_{FC} = 250 \cdot n_{stack} + 500 \tag{9}$$

Where n_{stack} is number of FC stacks used in the FCHEV and the values were taken from [53]. This yields an energy density of 100 W kg^{-1} for the FCS.

$$W_{TH_2} = 10 + 36.446 \cdot m_{H_2} \tag{10}$$

Where m_{H_2} is the mass capacity of the hydrogen tanks. This equation yields a maximum efficiency of storage of 2.74%.

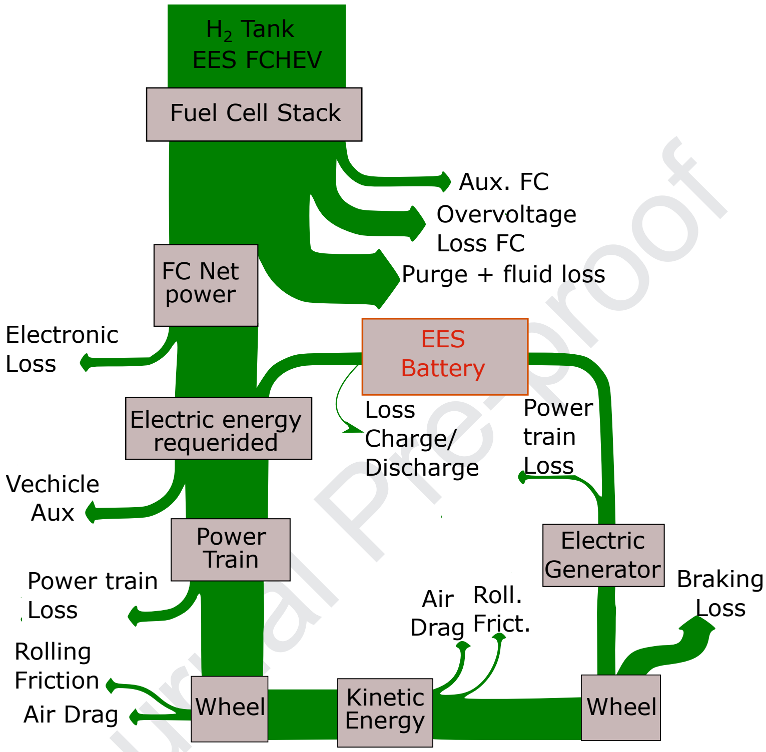

Figure 7: Schematic Sankey FCHEV

The stack voltage in the FC (V_{FC}) is obtained as the difference of the ideal Nernst's voltage (E) and the overvoltages sum ($\sum \eta$), shown in following equation (11).

$$\eta_{FC} = \eta_{act} + \eta_{conc} + \eta_{ohm} \tag{11}$$

Where (η_{act}) is the activation overvoltage, (η_{conc}) is the concentration overvoltage and (η_{ohm}) the ohmic overvoltage

The energy balance with their associated losses for the FCHEV is represented in the eq. 12.

$$ESS_{FCHEV} = EW + PT_{loss} + Veh.Aux + FC_{net} - ERB_{net} - B_{loss_out} \tag{12}$$

Where the FC_{net} is computed in the following eq. (13)

$$FC_{net} = LHV \cdot m_{H_2} - \eta_{FC} - Aux.FC - PurgeFC \tag{13}$$

The BEV has a battery pack with 56 cells of 30 Ah in series, with a nominal cell voltage of 3.7 V. The stack had a nominal voltage of 207.2 V, a maximum discharge current of 600 A, and a maximum charge current of 60 A (2C). The maximum and minimum SoD were set as 80% and 10% which gives a 70% depth of discharge (DOD). According with previous works, the specific energy of the battery is assumed to be 126 W h kg^{-1} having only a DOD of 70% [54, 55]. The regenerative brake can charge the battery if the

SoD is higher than the initial value. The stack has a nominal energy of 6.22 kWh. The battery stacks are connected in parallel to increase the range of the bus keeping a constant voltage.

The powertrain weight of the BEV is described by the following equation:

$$W_{PT} = W_{FC} + W_{BAT} + W_{EM} \tag{14}$$

The weight of the batteries is computed using the following equation:

$$W_{BAT} = 4.25 + 1.15 \cdot N_{Bat} \cdot Q_{Bat} \tag{15}$$

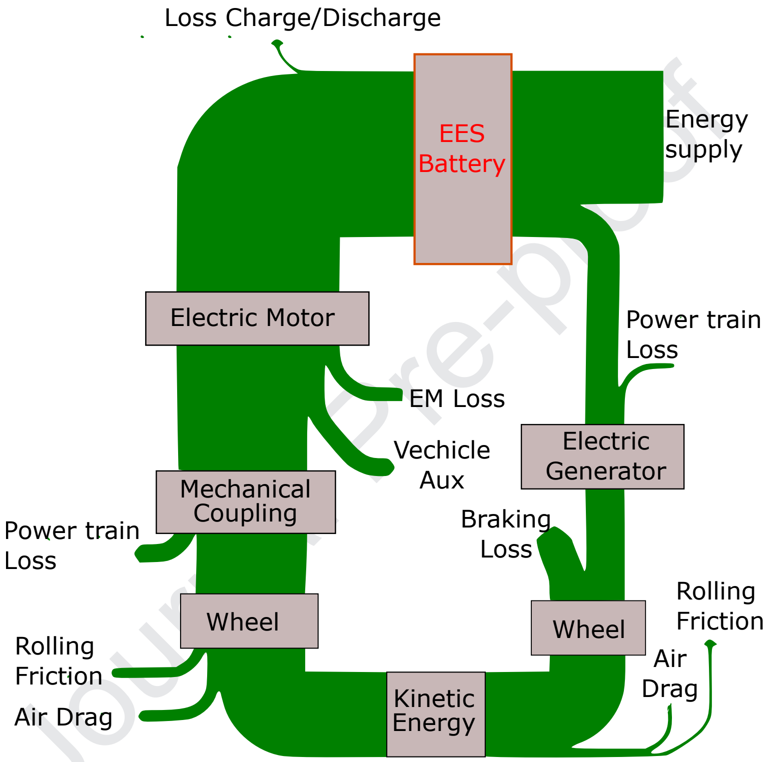

Figure 8: Schematic Sankey BEV

$$ESS_{BEV} = EW + PT_{loss} + Veh.Aux - ERB_{net} - B_{loss_out} \tag{16}$$

Table 3, shows the weights of FCHEV and BEV in all the cycles and ranges, where empty bus refers to vehicle bodywork.

2.6.4. Driving cycles

Since different driving patterns modify the energy consumption of the vehicles [56] two driving cycles were proposed for this study, the NEDC cycle with the EUDClow [57] variant (from now on referred to as EUDC) and the UK-BUS cycle [58]. Figure 9 shows the two driving cycles speeds. The UK-BUS cycle is a real life bus cycle, with multiple starts and stops where the maximum speed is fairly low. The EUDC cycle has a high maximum speed and less starts and stops, characteristics of interurban driving.

In the table 4 relevant parameters of the driving cycle are shown. It can be seen that the EUDC cycle has bigger maximum speeds and average driving speed while the UK BUS cycle shows a greater positive kinetic energy which means that a greater rate of motor power is needed to accelerate the vehicle.

Table 3: Weights in kg of the FCHEV and BEV in all the cycles

Cycle range	FCHEV bus				BEV bus	
	FCS	BAT	H_2	Total	BAT	Total
UK100	750	108	209	15621	1404	15659
EUDC100	1000	385	166	16105	1138	15393
UK200	750	108	420	15832	2988	17242
EUDC200	1000	385	329	16268	2338	16592
UK300	750	108	638	16051	4854	19109
EUDC300	1000	385	497	16436	3662	17916
UK400	750	108	864	16277	7143	21397
EUDC400	1000	385	665	16603	5145	19399

Cycle	Time [s]	Distance [m]	Max.Speed [$\mathrm{km\,h^{-1}}$]	ADS[1] [$\mathrm{km\,h^{-1}}$]	PKE[2] [$\mathrm{m\,s^{-3}}$]
EUDC	1224	10584.39	90.00	42.38	0.1859
UK BUS	3292	12125.17	41.96	13.30	0.3932

Table 4: Driving cycle parameters

Even though this cycles were not developed specifically for the locations used in this study, they achieve to represent two standard driving conditions for buses which is one of the interest of this study. Although the average all electric range (AER) for light-duty models is approximately 200 km [54], in this work, ranges up to 400 km are used to analyze each vehicle at the end of its ranges (100 km to 400 km) .

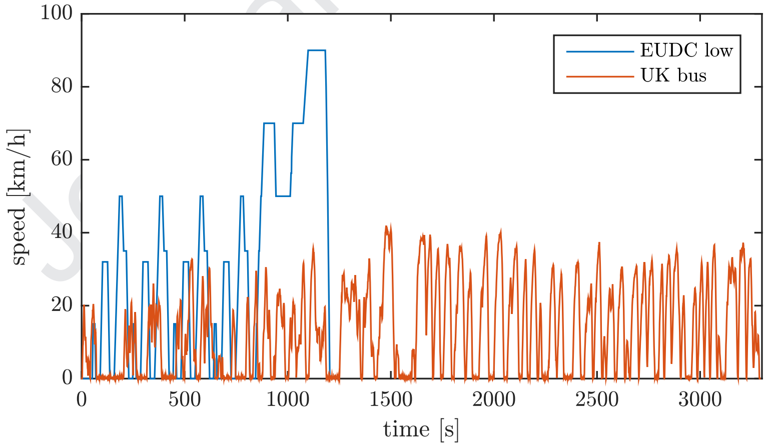

Figure 9: Driving cycles

2.7. TTW analysis 2030

Since the batteries and FC are still under development phase [59], the technological innovations of these systems will lead to being much more efficient, and consequently improve the indexes analyzed in this paper, such as: CT, VGE, TEE and FE. In this work, in line with specific literature [55, 60], the BEV raises its VGE because it is assumed that the energy density of LIBs increases up to 320 $\mathrm{W\,h\,kg^{-1}}$ by 2030.

[1] Average driver speed
[2] Positive kinetic energy

	2017			2030		
	Electricity	Diesel	H2	Electricity	Diesel	H2
CO	0.437	0.051	0.159	0.149	0.054	0.064
NOx	1.097	0.110	0.289	0.536	0.112	0.136
Eff.	0.442	0.859	0.562	0.535	0.895	0.637

Table 5: Argentina WTT results

	2017			2030		
	Electricity	Diesel	H2	Electricity	Diesel	H2
CO	0.300	0.050	0.098	0.284	0.053	0.078
NOx	0.220	0.109	0.135	0.093	0.111	0.093
Eff.	0.615	0.854	0.664	0.673	0.891	0.671

Table 6: Brazil WTT results

The CT is assumed to decrease in the future (2030 scenario) by performing fast overnight charges up to 5C, followed by a stabilization charge, that will amount to a charge of one hour and twenty minutes.

The U.S. DOE estimates that the FCS specific power will increase up to 650 $\mathrm{W\,kg^{-1}}$ by 2030 [59, 61].

The hydrogen storage systems are expected to increase their weight efficiency up to a 7%, leading to a substantial decrease in the system's weight [61, 62].

3. Results

3.1. WTT result

The results for the present and future scenarios and for the different countries are shown in tables: 5, 6 and 7. From the tables, it can be seen that the addition of RES to the electricity mix in each country improves both, the emissions and the efficiency, except in the case of the NOx emissions from Chile, where an increase is observed due to oil fired power plants increment. In tables 5 and 6, it can be seen that the addition of biodiesel to the blend increases the efficiency of the energy vector, but it also increases the emissions from its production. Lastly, it can be seen that the efficiency of the pathway for the production of hydrogen increases with the introduction of generation of hydrogen trough electrolysis powered with wind power. Also, the emissions are reduced, except in the case of NOx in Chile, where the increment in emissions in the electricity influences the emission rate in the hydrogen production.

3.2. TTW result

Table 8 summarizes the results obtained from the simulations carried out for each bus, each cycle and each range. Each column shows relevant information to analyze the performance of each powertrain also some of the relevant indexes for the TTW step are presented (see section 2.1). The abbreviations used and

	2017			2030		
	Electricity	Diesel	H2	Electricity	Diesel	H2
CO	0.237	0.050	0.137	0.136	0.050	0.074
NOx	0.861	0.143	0.283	1.566	0.143	0.312
Eff.	0.455	0.844	0.542	0.454	0.844	0.593

Table 7: Chile WTT results

Table 8: TTW result

		VGW [kg]	PSW [kg]	FW [l] [kg]	ESS [kWh]	EC loss [kWh]	ERRBnet [kWh]	EBout [kWh]	ICEloss [kWh]	Total loss [kWh]	WE [kWh]	Range [km]	TEE	FE [km/kWh]	VGE [kWh/kg]
	Diesel	15389.0	876.0	53.0	528.4	0.0	0.0	0.0	362.1	416.5	112.0	100.2	0.212	0.190	0.466
UK	HEV	15031.0	420.4	51.0	452.9	0.0	29.0	28.4	309.5	369.5	112.4	100.1	0.248	0.220	0.585
100	FCHEV	15621.3	1366.9	11.2	372.0	187.5	35.5	34.3	0.0	298.2	109.5	99.4	0.294	0.267	0.272
	BEV	15658.7	1404.3	0.0	184.4	3.8	39.6	220.5	0.0	113.6	110.8	100.5	0.601	0.545	0.131
	Diesel	15389.0	876.0	105.0	1046.5	0.0	0.0	0.0	716.0	823.4	223.2	200.0	0.213	0.191	0.922
UK	HEV	15031.0	420.4	102.0	906.6	0.0	58.4	55.8	619.2	740.1	224.9	200.6	0.248	0.221	1.169
200	FCHEV	15832.2	1577.8	22.7	756.8	383.3	71.8	69.6	0.0	606.5	222.7	200.0	0.294	0.264	0.480
	BEV	17242.0	2987.6	0.0	392.8	4.2	86.3	475.3	0.0	236.4	243.1	200.9	0.619	0.512	0.131
	Diesel	15389.0	876.0	157.3	1568.3	0.0	0.0	0.0	1072.4	1233.3	335.0	300.1	0.214	0.191	1.382
UK	HEV	15031.0	420.4	152.7	1357.0	0.0	87.6	83.1	926.5	1107.6	337.0	300.4	0.248	0.221	1.748
300	FCHEV	16050.5	1796.1	34.7	1155.0	588.2	108.6	104.8	0.0	925.5	338.7	300.0	0.293	0.260	0.643
	BEV	19108.7	4854.3	0.0	638.6	4.7	140.6	775.0	0.0	377.4	402.2	300.6	0.630	0.471	0.132
	Diesel	15389.0	876.0	209.5	2088.8	0.0	0.0	0.0	1427.9	1641.9	446.9	400.1	0.214	0.192	1.841
UK	HEV	15031.0	420.4	204.2	1814.5	0.0	116.8	111.1	1239.5	1481.9	449.5	400.6	0.248	0.221	2.338
400	FCHEV	16276.5	2022.1	47.0	1567.2	802.8	146.1	141.1	0.0	1256.4	458.0	400.1	0.292	0.255	0.775
	BEV	21397.1	7142.7	0.0	939.9	5.3	204.5	1139.6	0.0	545.8	599.0	400.8	0.637	0.426	0.132
	Diesel	15389.0	876.0	38.5	383.8	0.0	0.0	0.0	253.3	276.5	107.3	100.3	0.280	0.261	0.338
EUDC	HEV	15031.0	420.4	36.9	328.1	0.0	30.7	28.5	210.4	258.0	100.8	100.1	0.304	0.302	0.426
100	FCHEV	16105.1	1850.7	8.8	294.0	145.7	21.7	21.0	0.0	213.1	102.8	99.3	0.350	0.338	0.159
	BEV	15392.5	1138.1	0.0	149.3	5.1	21.3	166.0	0.0	70.4	100.6	100.2	0.674	0.671	0.131
	Diesel	15389.0	876.0	76.0	758.2	0.0	0.0	0.0	499.0	544.6	213.6	200.0	0.282	0.264	0.668
EUDC	HEV	15031.0	420.4	74.3	659.9	0.0	63.4	56.0	422.5	522.4	200.8	200.0	0.303	0.301	0.855
200	FCHEV	16267.9	2013.5	17.7	591.0	293.0	42.6	42.6	0.0	427.3	208.2	199.5	0.352	0.337	0.294
	BEV	16592.1	2337.7	0.0	307.3	6.6	44.9	346.1	0.0	140.8	211.9	200.1	0.690	0.651	0.131
	Diesel	15389.0	876.0	114.2	1138.4	0.0	0.0	0.0	749.7	818.3	320.1	300.2	0.281	0.264	1.003
EUDC	HEV	15031.0	420.4	112.4	998.2	0.0	98.2	83.7	639.4	795.6	300.9	300.0	0.301	0.300	1.289
300	FCHEV	16435.7	2181.3	26.9	897.0	444.8	65.6	64.4	0.0	648.8	315.4	300.4	0.351	0.335	0.411
	BEV	17916.0	3661.6	0.0	481.6	7.2	73.5	548.5	0.0	218.8	336.9	300.4	0.700	0.624	0.132
	Diesel	15389.0	876.0	152.0	1515.1	0.0	0.0	0.0	996.9	1087.9	427.2	400.1	0.282	0.264	1.335
EUDC	HEV	15031.0	420.4	149.8	1331.2	0.0	131.1	111.6	852.2	1061.0	401.4	399.9	0.301	0.300	1.719
400	FCHEV	16603.4	2349.0	36.1	1203.1	597.3	87.2	86.0	0.0	869.5	423.1	399.7	0.351	0.332	0.512

their meaning are as follows: VGW is the Vehicle gross weight, PSW is powertrains components weight, FW is the fuel weight expressed in kg for gaseous fuel and in l for liquid fuel, ESS is the energy stored in the systems, ECloss is the total electrochemical loss of the FC, ERRBnet is the net energy recovered to the battery through regenerative braking, EBout is the energy that the battery lost during the discharge, ICEloss is the energy lost in the ICE, Total loss is the sum of all the losses along the pathway and the vehicles auxiliaries energy, and WE is the required wheels energy.

Figure 10 shows the results of the FE index, where it is can see that for short distances the BEV predominates over the other vehicles. On the other hand, as the range increases, the other configurations remain fairly constant while the BEV substantially decreases its FE reaching less than 0.6 km/kWh for the EUDC cycle and almost 0.4 km/kWh for the UK cycle. Regarding the difference between cycles, the ICE buses have the greater FE difference between cycles. This is because, as it was said in section 2.6.4, the UK is a clearly an urban cycle with many stops and accelerations, whereas the EUDC cycle represents an interurban cycle, therefore in the EUDC cycle much less energy is lost in the acceleration. However, for the electric vehicles (BEV and FCHEV) this difference is lower due to the high performance of the electric motor throughout its RPM range.

As can be seen in Figure 11, the FE difference between EUDC and UK for a range of 100 km is close to 37% for DV and HEV, while for the FCHEV and BEV it is 26% and 23% respectively. As the range increases (400 km) the FE of the BEV decreases and the difference in FE between cycles increases, it can seen that the FE difference between the EUDC and the UK is higher (38%), equating to the DV and above the HEV (37%) and the FCHEV (30%).

In the TTW Total Energy Efficiency (Figure 12) is shown that the BEV is the most efficient system followed by the FCHEV. Increasing the range slightly increases the index for the BEV, remaining practically unchanged for the other configurations. For the analysis between cycles, the buses perform better in the EUDC cycle, and the ratio between the TEE of the cycles for different ranges remains practically constant.

The VGE index (Figure 13) is clearly dominated by vehicles with ICEs. The Uk cycle allows the buses to have better indexes except for the BEV, which is the same for both cycles. This is because the maximum speeds of the UK cycle are lower than in the EUDC cycle and therefore the sizing of the power systems is lower and consequently the weights are lower (see tables 8). Moreover the UK cycle has a more aggressive driving pattern thus needing more energy expenditure per distance than that of the EUDC cycle, this forces the vehicles to store more energy, raising the VGE index. Also the DV, HEV and FCHEV systems improve their indexes substantially when the range increases, but not the BEV that remains unchanged.

In the case of the EI, it was decided to plot the two CO and NOx gases separately (see Figure 14) and show the CO and NOx emissions per distance [g/km], only of the vehicles with ICE (DV and HEV) since the ZEVs (FCHEV and BEV) do not have TTW emissions. For the DV, the NOx emissions in the UK cycle seem to double those produced in the EUDC cycle while the difference in CO emissions between the two cycles is not significant. However with an increased range, all the emissions decrease. On the other hand, for the HEV, there are higher CO emissions for the UK cycle and the NOx emissions seem to be quite equal for the two cycles. In addition, with the range increment, only the CO emissions in the UK cycle decrease, with NOx and CO remaining unchanged for other cycles and ranges.

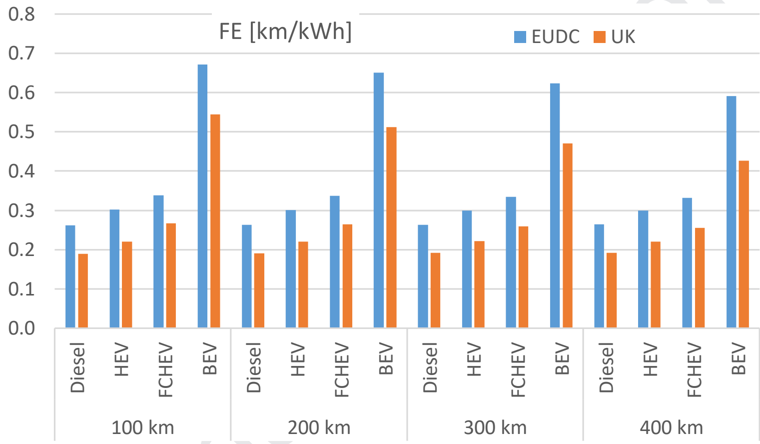

Figure 10: TTW Fuel Economy

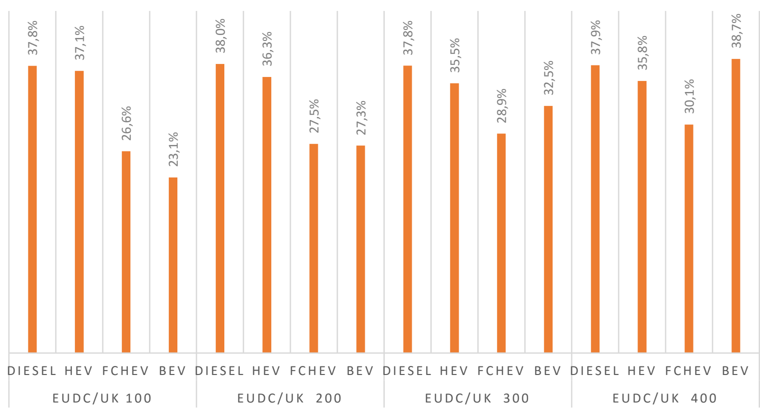

Figure 11: FE difference between EUDC and UK

3.3. WTW result

In this section the results of the WTW analysis are presented in the form of stacked bar charts. The normalization proposed in the section 4 is used in the indexes obtained in order to aid to the comparison between them.

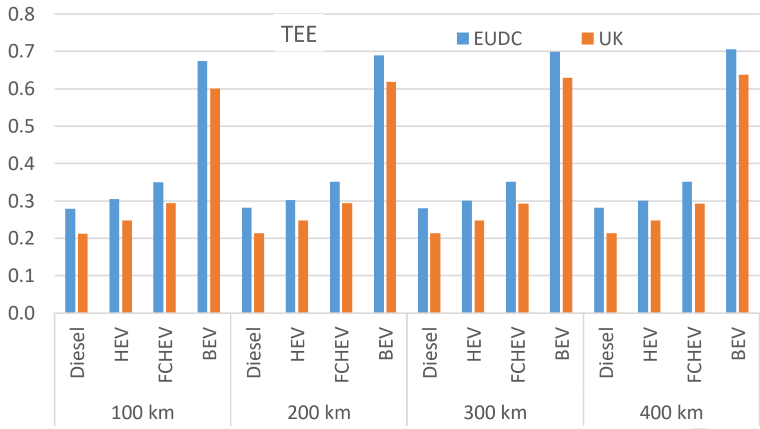

Figure 12: TTW Total Energy Efficiency

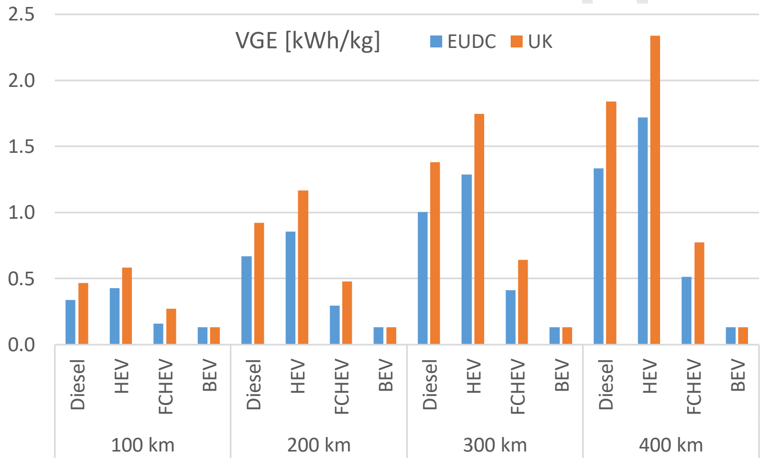

Figure 13: TTW Vehicle Gravimetric Energy

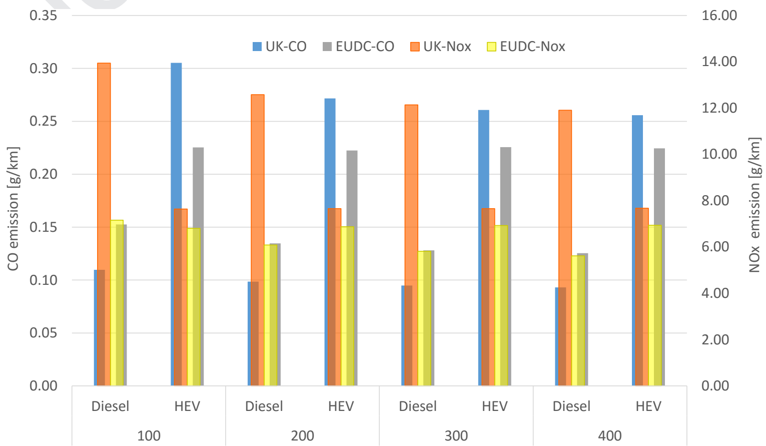

Figure 14: TTW CO & NOx emission

3.3.1. WTW Argentina 2017

As we can see in Figure 15 for short ranges (100 km) the BEV and FCHEV seem to be able to compete with the DV and HEV. In the long ranges (400 km) the vehicles with ICE offer significant comparative advantages with respect to the BEV and a little less with respect to the FCHEV in several indexes: CT and VGE especially. ZEVs become very noncompetitive because, compared to the others, the CT and the VGE indexes are very low and the EI index is also lower but to a lesser extent. The FCHEV, in comparison to BEVs, improves substantially for long ranges,in the VGE and the FE index. On the other hand, comparing between cycles, it can be seen that the BEVs seem to improve considerably compared to the other vehicles for the UK cycles.

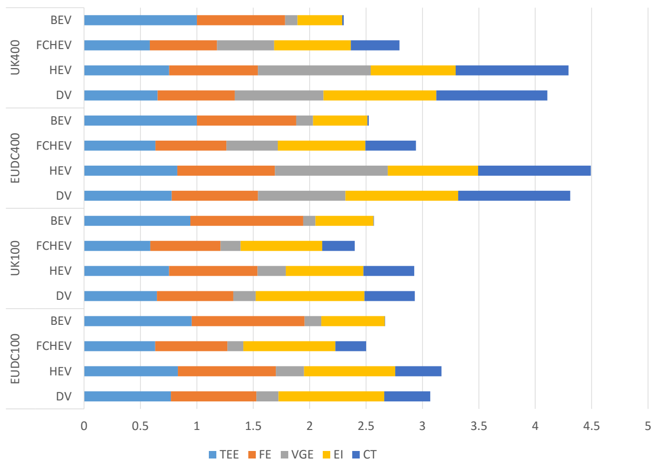

Figure 15: WTW Argentina 2017

3.3.2. WTW Argentina 2030

For the Argentina 2030 scenario (Figure 16), for short cycles (100 km range) the BEV and FCHEV seem to compete on an equal basis with the ICE Buses although they have a lower CT index (in particular BEV) but they improve notably in the EI index with respect to the 2017 scenario, even to the point of exceeding the performance of vehicles with ICE. For long cycles, the BEV lowers its performance substantially, whereas in comparison with 2017 the FCHEV seems to compete as equal with the DV and the HEV. For the different cycles we can see that, like the 2017 scenario, the DV decreases in the FE index more than the other vehicles for the UK cycle.

3.3.3. WTW Brazil 2017

In the scenario Brazil 2017 (Figure 17), due to the high percentage of hydropower, the BEV, and FCHEV to a lesser extent, have a great performance in almost all their indexes, except in the CT for the BEV. However, for long ranges (400 km) the EVs become much less competitive since not only the CT is very low, but also the VGE is considerably low. In the BEV, the EI also decreases below the levels of the DV. In contrast, the FCHEV has a slightly lower performance than DV and HEV in the CT and VGE indexes.

3.3.4. WTW Brazil 2030

In the 2030 scenario (see Figure 18) the BEV also has a great performance in general but not in the CT index which continues to be much lower than in the other vehicles. On the other hand, the FCHEV has

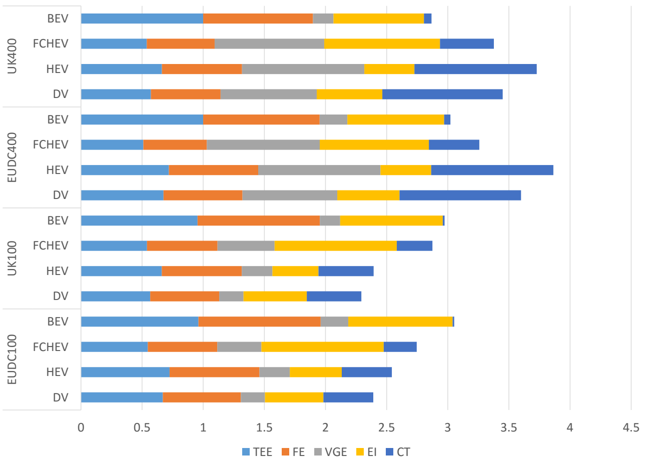

Figure 16: WTW Argentina 2030

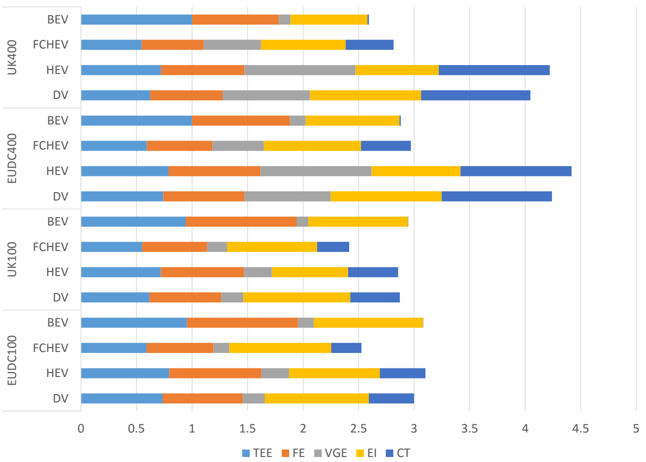

Figure 17: WTW Brazil 2017

similar performances to the two vehicles with ICEs, except that it has much better VGE and EI indexes. The ICE vehicles keep their advantage on CT in all ranges and cycles. For long ranges the ICE vehicles do not decrease their FE as the BEV does, but they still perform worse than the BEV.

3.3.5. WTW Chile 2017

As it can be seen in Figure 19 in this scenario there seems to be a great parity in the performance of the four powertrain configurations for short ranges (100 km). However, the BEV has, as in the case of Argentina and Brazil, a low CT index but unlike in Argentina, the EI index is competitive due to its electricity mix (see Figure 4). In contrast, for long ranges, the ICE vehicles have a clear advantage over the BEV due to

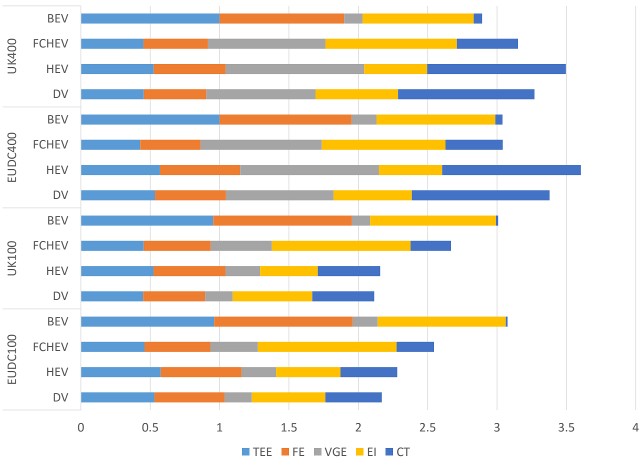

Figure 18: WTW Brazil 2030

the weight increase of the powertrains. The FCHEV has much better performance than the BEV although it is worse than that of the DV and the HEV.

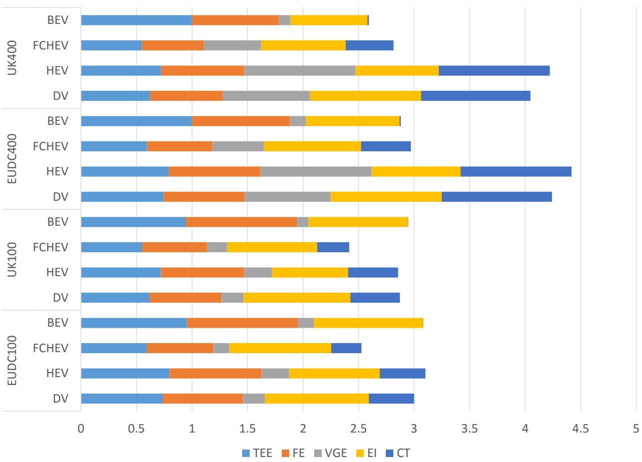

Figure 19: WTW Chile 2017

3.3.6. WTW Chile 2030

For the Chile 2030 scenario (Figure 20), the FCHEV has a high EI (such as the BEV), although in the other indexes, it is similar to that of the DV and HEV. The BEV keeps the worst performance in the CT index. For long ranges again as in the 2017 scenario the BEV has high EI, TEE and FE indexes although very low VGE and CT indexes. The FCHEV has high EI, TEE, VGE and FE indexes. In comparison with the BEV, the FCHEV has much better performances for the CT.

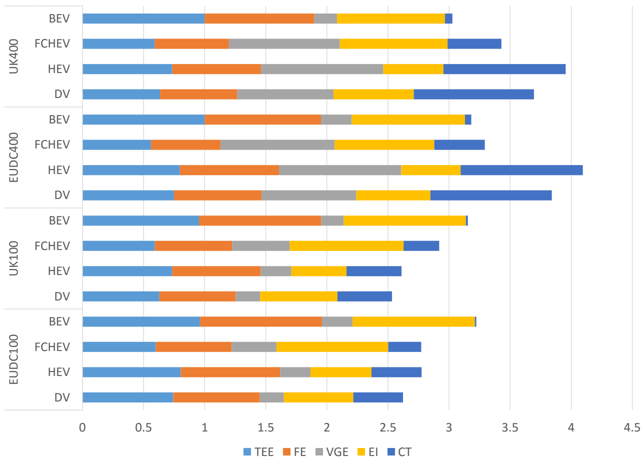

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Figure 20: WTW Chile 2030

4. Discussion

Seeking a unique index that allows a simpler comparative analysis of the energy and environmental sustainability of the different buses, an Integrated Sustainability Index (ISI) (Hacatoglu et. al [63]) is proposed. To normalize the indexes in the range from zero to one, the indexes evaluated in each scenario of each country were divided by the best indexes achieved in each country and scenario, i.e. the lower CT and the higher FE, TEE, EI, and VGE. That way an index with a value of one is the best possible performance for that country in that scenario. The value of the index is multiplied by its weighting factor and the ISI of the system is obtained as the sum of this values.

All weighting factors were chosen based in the criterion of the reference [64]. For the assignment of values, it is proposed, 0.4 for efficiency indicators, 0.4 for environmental indicators and 0.2 for operational indicators. Within the efficiency indicators the following values were assigned, 0.05 for TEE, 0.25 for FE and 0.1 for VGE.

As a rule, we emphasized that for the BEV powertrain within the WTW , TEE and FE indexes are always bigger than all other powertrains, regardless of the range, cycle type, year or country, meaning that energy conversion of this kind of powertrain is the most efficient and are able to cover distances with less energy. One exception occurs in Argentina for both cycles in the longest range where the FE of the BEV is almost equal to that of the HEV, while in the other powertrains the FE is lower. In general, electricity mixes that rely strongly on fossil fuels, such as Argentina and Chile in 2017, the DV and HEV have better EI indexes than electric vehicles. This is due to the fact that the electricity generation comes mainly from fossil fuels (around 60%) with conversion technologies that can be improved, such as the conversion from single cycle to combined cycle in natural gas power stations. Adding to that, the power losses due to transmission and distribution oscillate between 15.78% and 6.54%. In the case of Argentina, far more than for the other countries, the change from one scenario to another generates an important impact on their ISI indexes, favoring electric mobility in the future scenario (see Figure 21). In 2017 it can be seen that the ICE vehicles are better for both cycles and for all ranges. On the other hand, in 2030 for short ranges, BEVs are better than the DV and HEV while the FCHEV is clearly dominant in all the ranges and cycles, mainly due to the BEV lower yield in the EI, VGE and CT indexes. In Brazil (Figure 22), due to its predominantly non-fossil electricity mix, FCHEV and BEV, to a lesser extent, have better ISI indexes for short trips in the 2017 scenario. For long ranges, the BEV greatly diminishes its performance, far more in the UK-BUS driving cycle, however the DV has its best indexes in those ranges. In the 2030 scenario, the BEVs dominate in all ranges for the EUDC cycle and for the UK cycle for the shortest range, for higher ranges the FCHEV is better. In the case of Chile (Figure 23) the ISI results are much more similar to the Argentine case than to the Brazilian case, especially for the current scenario (2017). The substantial difference is that for shortest range (100 km) the BEV obtains the best result for the EUDC cycle, yielding a good result in the UK cycle. In contrast, for long ranges, the ICE powertrains dominate (DV and HEV). On the other hand, for future scenarios (2030), up to 200 km of range the BEV clearly dominates, followed closely by the FCHEV. For intermediate ranges between 200 kmand 300 km the FCHEV seems to have the best performance. This result in the 2030 scenario is mainly due to the introduction of RES in the electricity mix. Instead for ranges greater than 400 km the HEV and DV for the EUDC cycle and the DV for UK cycles have the best results.

	EUDC				UK BUS			
	DV	HEV	FCHEV	BEV	DV	HEV	FCHEV	BEV
Range	ISI ARGENTINA 2017							
100km	0.70	0.69	0.59	0.54	0.70	0.62	0.55	0.51
200km	0.79	0.76	0.61	0.52	0.78	0.72	0.57	0.49
300km	0.86	0.83	0.63	0.50	0.83	0.78	0.58	0.45
400km	0.91	0.88	0.63	0.48	0.88	0.84	0.59	0.42
	ISI ARGENTINA 2030							
100km	0.49	0.50	0.66	0.66	0.49	0.46	0.68	0.65
200km	0.57	0.57	0.67	0.65	0.56	0.55	0.71	0.64
300km	0.63	0.63	0.67	0.65	0.62	0.61	0.72	0.62
400km	0.68	0.68	0.69	0.64	0.66	0.66	0.72	0.60

Figure 21: ISI ARGENTINA 2017 & 2030

	EUDC				UK BUS			
	DV	HEV	FCHEV	BEV	DV	HEV	FCHEV	BEV
Range	ISI BRAZIL 2017							
100km	0.53	0.53	0.63	0.61	0.57	0.51	0.63	0.62
200km	0.62	0.60	0.65	0.59	0.65	0.60	0.65	0.58
300km	0.68	0.66	0.66	0.57	0.70	0.66	0.66	0.54
400km	0.73	0.72	0.67	0.54	0.75	0.71	0.66	0.50
	ISI BRAZIL 2030							
100km	0.47	0.47	0.63	0.69	0.47	0.44	0.65	0.68
200km	0.55	0.54	0.64	0.68	0.55	0.52	0.67	0.66
300km	0.61	0.60	0.64	0.67	0.60	0.59	0.69	0.64
400km	0.66	0.66	0.66	0.66	0.65	0.64	0.69	0.62

Figure 22: ISI BRAZIL 2017 & 2030

5. Conclusion

In the search for possible analyses between different configurations of vehicles and energy vectors, taking into account the impact of the electricity mix, the different driving patterns and the ranges of said vehicles, this work developed a comparative study taking a single sustainability index to perform the evaluation of the vehicles. The results showed that, within the zero emission vehicles (ZEVs), the BEV technology is the most efficient alternative for short ranges and the FCHEV technology for long ranges, for the future

	EUDC				UK BUS			
	DV	HEV	FCHEV	BEV	DV	HEV	FCHEV	BEV
Range	ISI CHILE 2017							
100km	0.69	0.68	0.62	0.71	0.69	0.61	0.57	0.67
200km	0.78	0.75	0.63	0.68	0.77	0.71	0.60	0.63
300km	0.85	0.82	0.66	0.66	0.82	0.77	0.61	0.58
400km	0.90	0.87	0.66	0.62	0.87	0.82	0.61	0.54
	ISI CHILE 2030							
100km	0.54	0.55	0.64	0.73	0.55	0.51	0.67	0.72
200km	0.62	0.62	0.65	0.71	0.63	0.60	0.70	0.70
300km	0.69	0.69	0.66	0.71	0.68	0.66	0.71	0.68
400km	0.74	0.74	0.67	0.69	0.73	0.72	0.71	0.66

Figure 23: ISI CHILE 2017 & 2030

scenarios studied. Because the BEVs are markedly superior in the TTW, actions to improve their energy and environmental performance should focus on how to generate electricity, with what electricity mix and with what technologies. The FCHEV powertrains became competitive within the WTW scope with the introduction of 50% of H_2 from wind powered water electrolysis. In this case it's showed that FCHEV is the best alternative for emissions reduction in the three countries. Brazil, with its 81 % of RES in its electricity mix, is ideal for the application of FCHEV and BEV buses, even in the current scenario. Although, for the construction of the 2030 scenario the ICE TTW technologies were the same as those of the 2017 scenario, the improvements in the performance of ICE vehicles, may come from the use of alternative fuels, such as biodiesel, ethanol or hydrogen, and can lead to lower environmental impacts due to improvements not only in vehicle technology, but also in the fuel production cycle.

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We compare different buses powertrains using energy and environmental analysis
The study is framed to Argentina, Brazil and Chile and performed for 4 different buses
The study was made for present (2017) and future (2030) scenarios
We use 2 different standard driving cycles and 4 ranges
An index to compare the energy and environmental sustainability is used

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: