Energy 187 (2019) 115906

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

G. Correa [a, *], P.M. Muñoz [a], C.R. Rodriguez [b]

[a] CONICET - CITCA, Universidad Nacional de Catamarca - FACEN, Prado 366, K4700BDH, Catamarca, Argentina
[b] Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Av.Velez Sarsfield 1611, X5016GCA, Córdoba, Argentina

A R T I C L E I N F O

Article history:
Received 2 July 2019
Received in revised form
31 July 2019
Accepted 6 August 2019
Available online 9 August 2019

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

A B S T R A C T

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.

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

* Corresponding author.
E-mail address: correa.gabriel@conicet.gov.ar (G. Correa).

https://doi.org/10.1016/j.energy.2019.115906
0360-5442/

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
FCHEV	Fuel cell hybrid electric vehicle
FCS	Fuel cell system
FE	Fuel economy
GHG	Green house gases
H2	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

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 Fig. 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).

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.

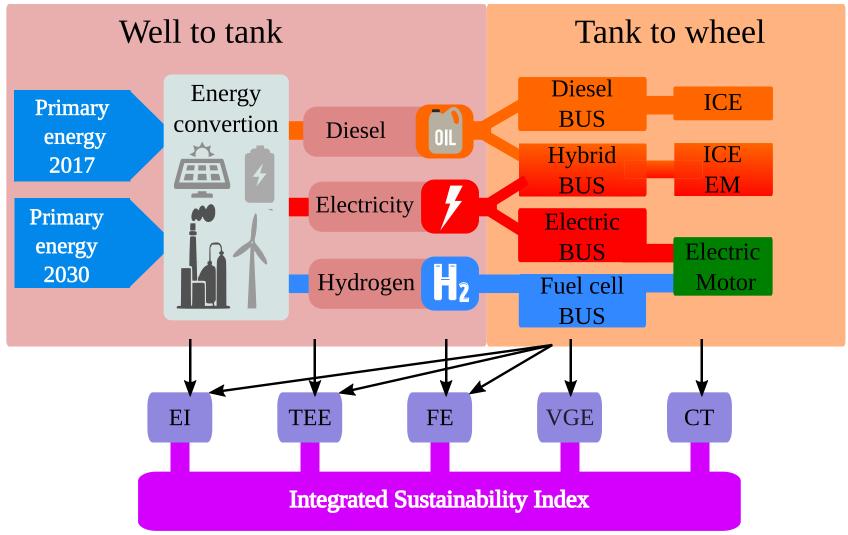

Fig. 1. WTW analysis diagram.

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 refueling 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 h [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 h 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 L 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 Figs. 2–4, 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].

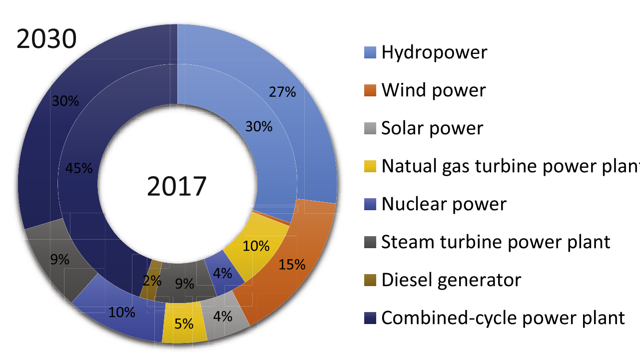

Fig. 2. Electricity mix Argentina.

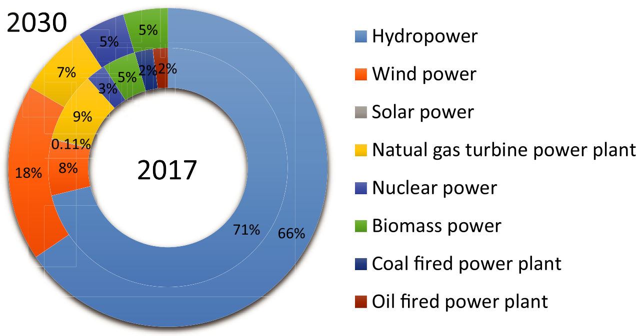

Fig. 3. Electricity mix Brazil.

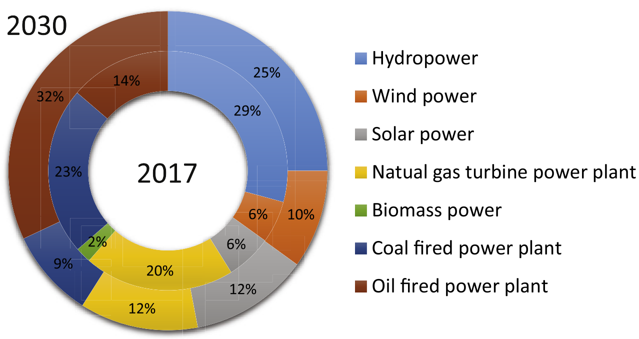

Fig. 4. Electricity mix Chile.

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 Fig. 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].

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 (920000 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 Fig. 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 (Fig. 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.

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].

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 equation (1).

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

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

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

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

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

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. 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 Fig. 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 equations (5) and (6), with their associated losses.

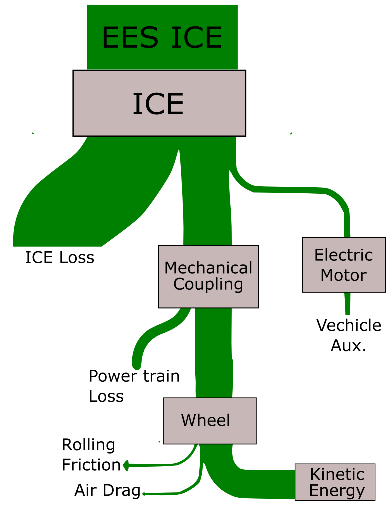

Fig. 5. Schematic sankey for the ICEV

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

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 Fig. 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} (eq. (7)) are the powertrain losses which includes: $Mech_{loss}$, EM_{loss}

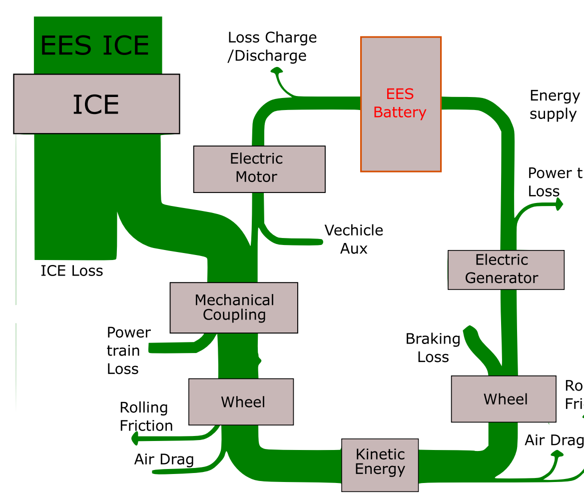

Fig. 6. Schematic sankey HEV

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

the electric motor loss and $Elect_{loss}$ the electronic losses (DC/DC, DC/AC and controllers).

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

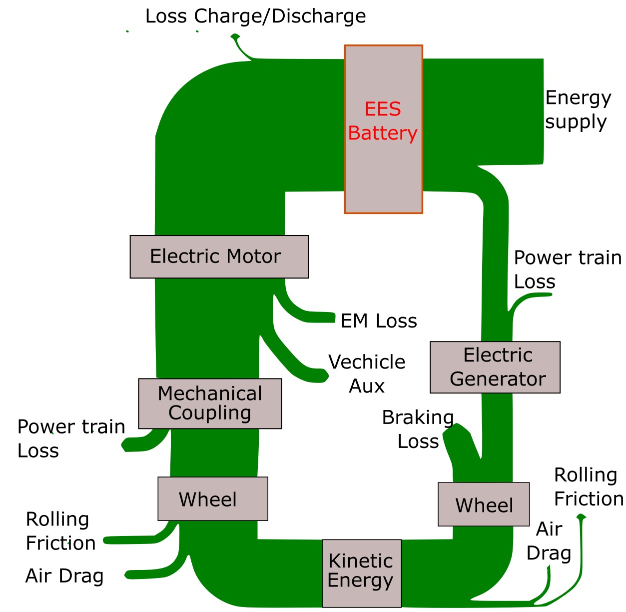

Fig. 8. Schematic sankey BEV

2.6.3. BEV and FCHEV buses models description

In Figs. 7 and 8, the sankey diagrams of FCHEV and BEV are shown respectively. 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 $100 \mathrm{W kg}^{-1}$ 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%.

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).

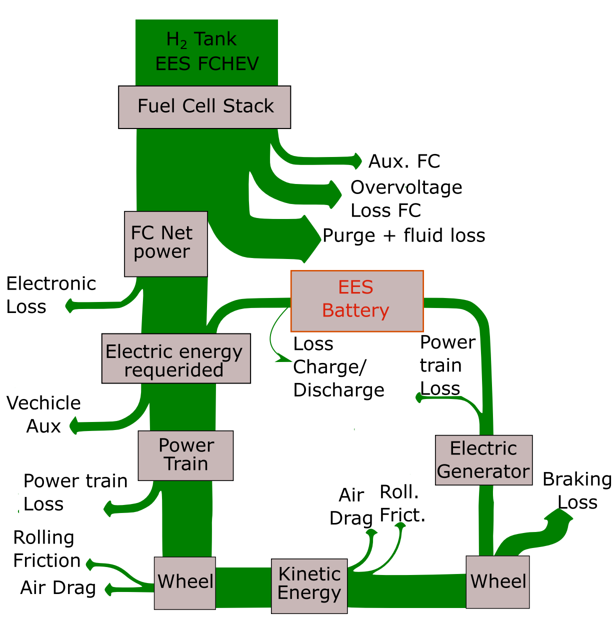

Fig. 7. Schematic sankey FCHEV

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

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 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 $126 \mathrm{W\,hkg}^{-1}$ 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:

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

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

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

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

Cycle range	FCHEV bus				BEV bus	
	FCS	BAT	H2	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

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]. Fig. 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 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.

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–400 km).

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 320W hkg^{-1} by 2030.

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 1 h and 20 min.

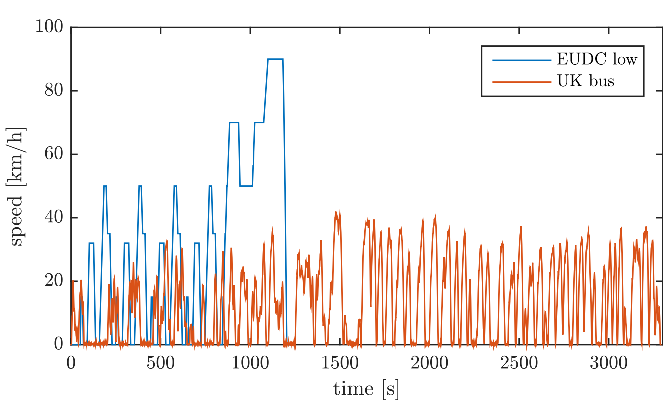

Fig. 9. Driving cycles.

The U.S. DOE estimates that the FCS specific power will increase up to 650Wkg^{-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 (see Table 7).

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 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.

Fig. 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 Fig. 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 (Fig. 12) is shown that the BEV is the most efficient system followed by the FCHEV. Increasing

Table 4
Driving cycle parameters.

Cycle	Time	Distance	Max.Speed	ADSAverage driver speed	PKEPositive kinetic energy
	[s]	[m]	[km h^{-1}]	[km h^{-1}]	[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 5
Argentina WTT results.

	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 6
Brazil 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 7
Chile WTT results.

	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

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 (Fig. 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 Table 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 Fig. 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.

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 section 4 is used in the indexes obtained in order to aid to the comparison between them.

3.3.1. WTW Argentina 2017

As we can see in Fig. 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.

3.3.2. WTW Argentina 2030

For the Argentina 2030 scenario (Fig. 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 (Fig. 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 Fig. 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 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

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]
UK 100	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
	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
	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
UK 200	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
	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
	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
UK 300	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
	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
	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
UK 400	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
	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
	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
l)2−16 EUDC 100	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
	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
	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
EUDC 200	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
	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
	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
EUDC 300	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
	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
	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
EUDC 400	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
	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
	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

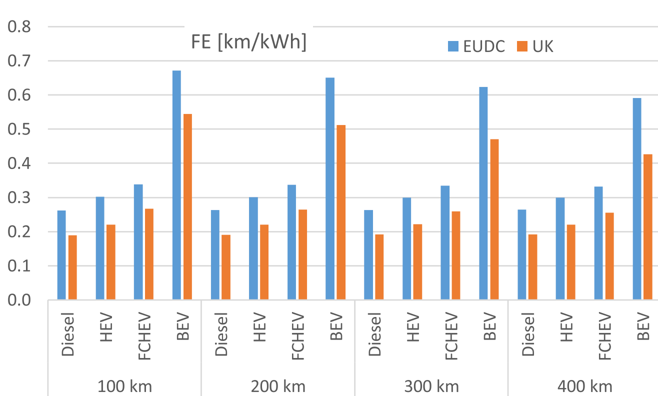

Fig. 10. Ttw fuel economy.

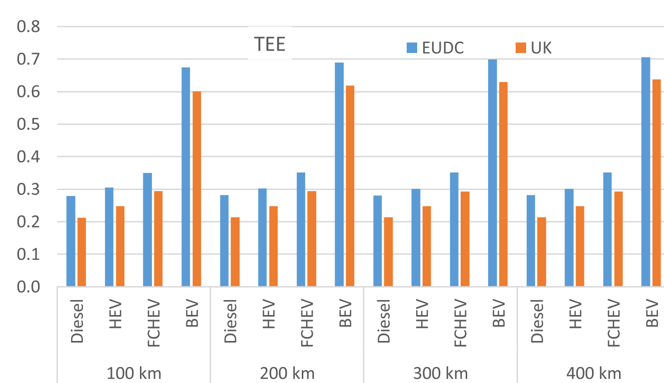

Fig. 12. Ttw total energy efficiency.

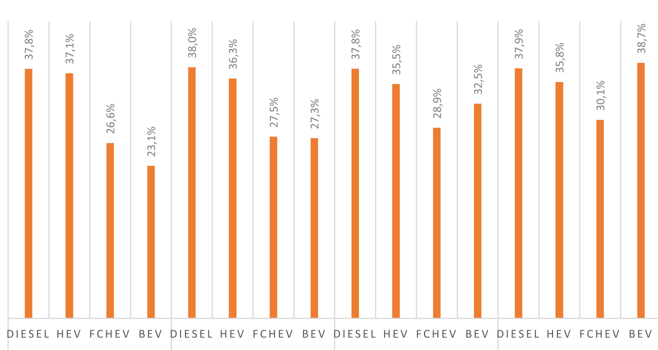

Fig. 11. FE difference between EUDC and UK.

still perform worse than the BEV.

3.3.5. WTW Chile 2017

As it can be seen in Fig. 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 Fig. 4). In contrast, for long ranges, the ICE vehicles have a clear advantage over the BEV due to 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.

3.3.6. WTW Chile 2030

For the Chile 2030 scenario (Fig. 20), the FCHEV has a high EI

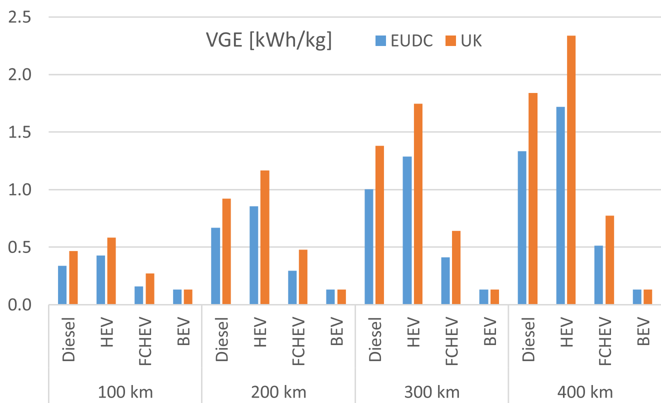

Fig. 13. Ttw vehicle gravimetric energy.

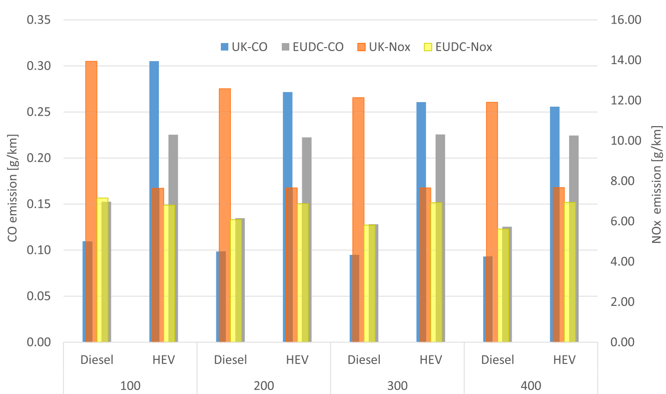

Fig. 14. TTW CO & NOx emission.

(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.,

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 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

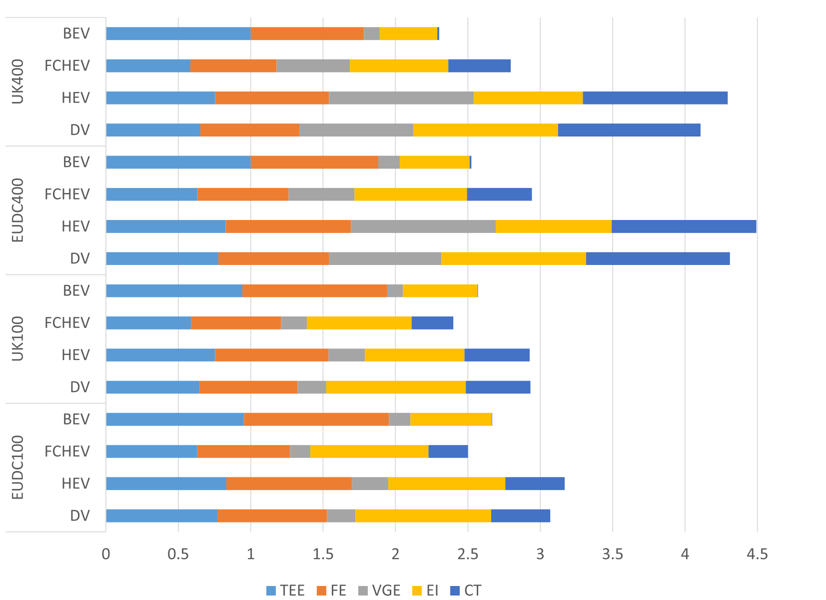

Fig. 15. Wtw Argentina 2017.

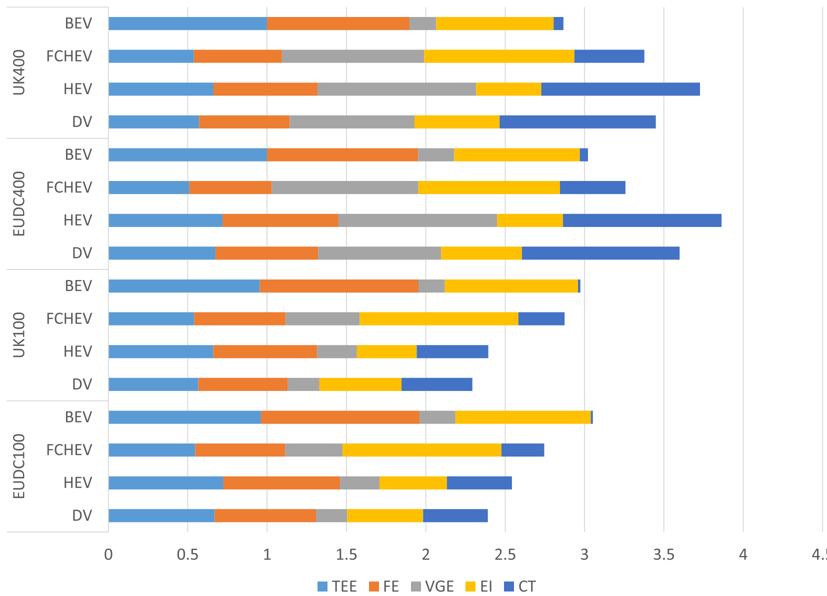

Fig. 16. Wtw Argentina 2030.

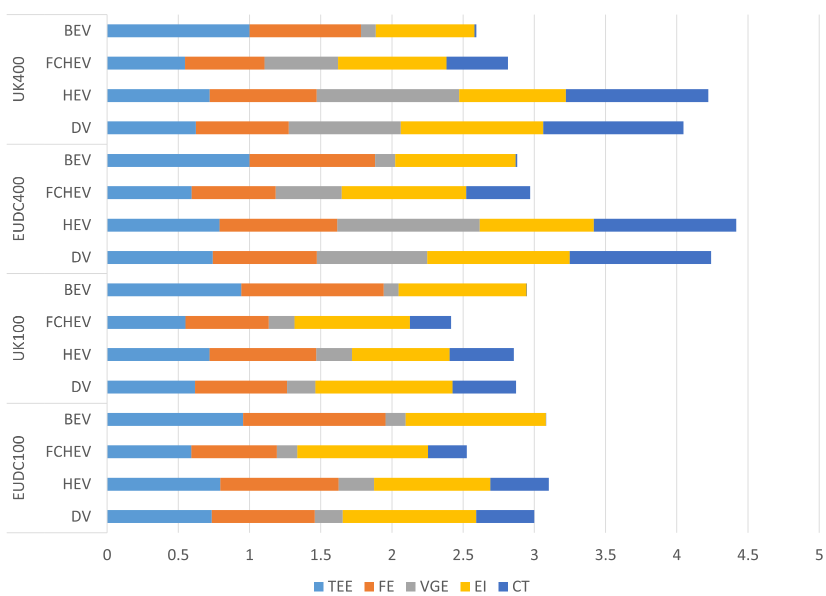

Fig. 17. Wtw Brazil 2017.

generates an important impact on their ISI indexes, favoring electric mobility in the future scenario (see Fig. 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 (Fig. 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 (Fig. 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 km and 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.

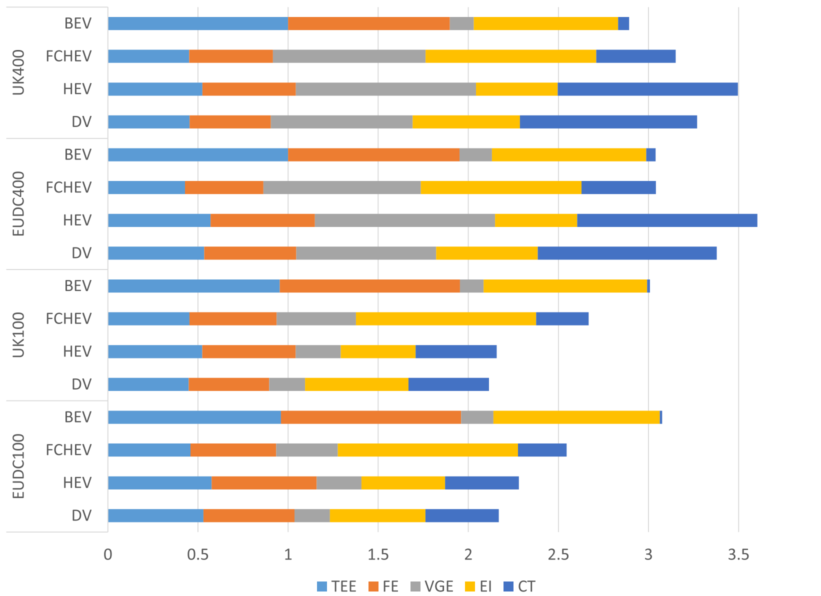

Fig. 18. Wtw Brazil 2030.

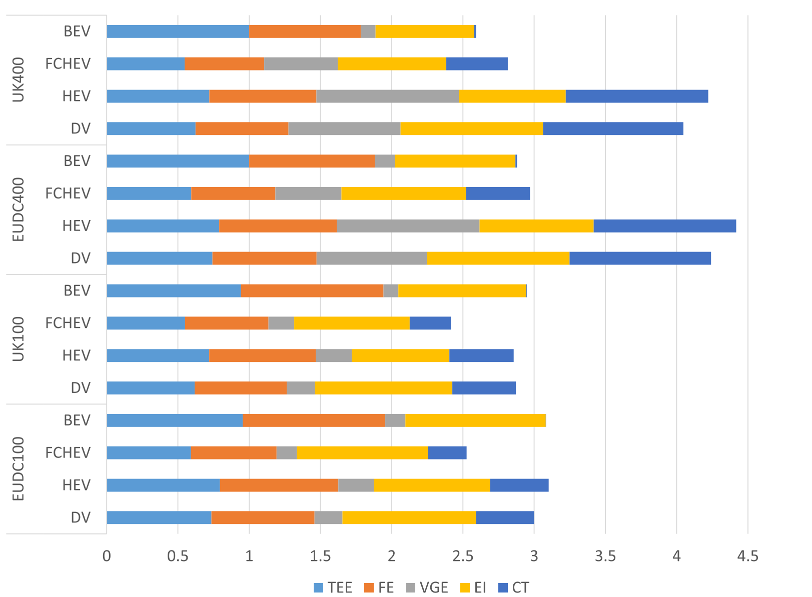

Fig. 19. Wtw Chile 2017.

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 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 H2 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.

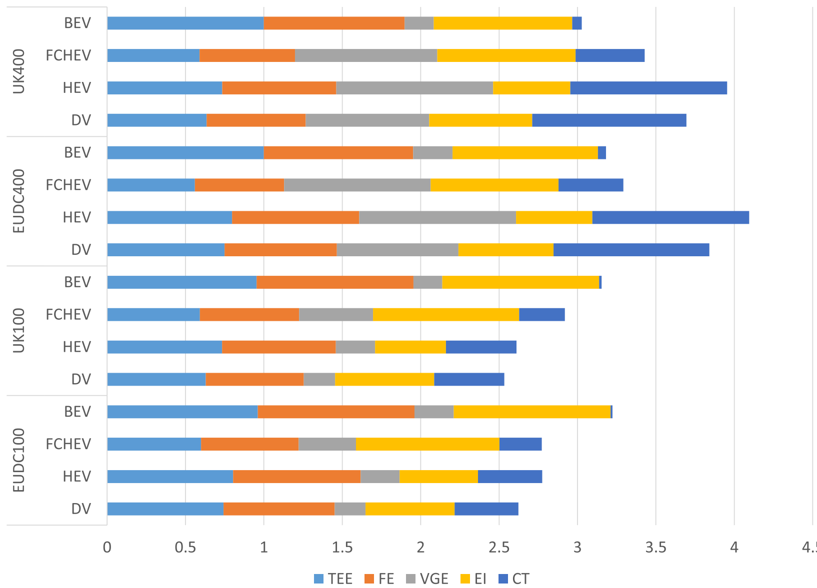

Fig. 20. Wtw Chile 2030.

	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

Fig. 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

Fig. 22. ISI Brazil 2017 & 2030.

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.

	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

Fig. 23. ISI Chile 2017 & 2030.

Acknowledgements

This work was partially supported by the National Agency of Scientific and Technological Promotion [PICT 2015 N∘0145] and CONICET [PIO N∘15920150100001CO]. The authors acknowledge the contribution of CONICET-UNCA, MINCyT, SECyT-UNC and the FCEFyN-UNC Aeronautical Department.

References

[1] García-Olivares Antonio, Solé Jordi, Osychenko Oleg. Transportation in a 100% renewable energy system. Energy Convers Manag 2018;158:266–85. https://doi.org/10.1016/J.ENCONMAN.2017.12.053. 2, https://www.sciencedirect.com/science/article/pii/S0196890417312050. ISSN 0196-8904.

[2] Grüger Fabian, Dylewski Lucy, Robinius Martin, Stolten Detlef. Carsharing with fuel cell vehicles: sizing hydrogen refueling stations based on refueling behavior. Appl Energy 2018;228:1540–9. https://doi.org/10.1016/J.APENERGY.2018.07.014. 10, https://www.sciencedirect.com/science/article/pii/S0306261918310419?via%3Dihub. ISSN 0306-2619.

[3] Alazemi Jasem, Andrews John. Automotive hydrogen fuelling stations: an international review. Renew Sustain Energy Rev 2015;48:483–99. https://doi.org/10.1016/J.RSER.2015.03.085. 8, https://www.sciencedirect.com/science/article/pii/S1364032115002385?via%3Dihub. ISSN 1364-0321.

[4] Giorgio Dispenza, Sergi Francesco, Giuseppe Napoli, Randazzo Nico, Di Novo Samuele, Micari Salvatore, Antonucci Vincenzo, Andaloro Laura. Development of a solar powered hydrogen fueling station in smart cities applications. Int J Hydrogen Energy 2017;42(46):27884–93. https://doi.org/10.1016/J.IJHYDENE.2017.07.047. 11, https://www.sciencedirect.com/science/article/

pii/S0360319917327842?via%3Dihub. ISSN 0360-3199.
[5] Yoo Eunji, Kim Myoungsoo, Han Ho Song. Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea. Int J Hydrogen Energy 2018;43(41):19267–78. https://doi.org/10.1016/J.IJHYDENE.2018.08.088. 10, https://www.sciencedirect.com/science/article/pii/S0360319918326296. ISSN 0360-3199.
[6] Hess Andrea, Malandrino Francesco, Reinhardt Moritz Bastian, Casetti Claudio, Hummel Karin Anna, Jose M, Barceló-Ordinas. Optimal deployment of charging stations for electric vehicular networks. In: Proceedings of the first workshop on Urban networking - UrbaNe '12. New York, New York, USA: ACM Press; 2012, ISBN 9781450317818. p. 1. https://doi.org/10.1145/2413236.2413238. http://dl.acm.org/citation.cfm?doid=2413236.2413238.
[7] Yazdanie Mashael, Noembrini Fabrizio, Dossetto Lionel, Boulouchos Konstantinos. A comparative analysis of well-to-wheel primary energy demand and greenhouse gas emissions for the operation of alternative and conventional vehicles in Switzerland, considering various energy carrier production pathways. J Power Sources 2014;249:333–48. https://doi.org/10.1016/j.jpowsour.2013.10.043. ISSN 03787753.
[8] Svensson Ann Mari, Møller-Holst Steffen, Glöckner Ronny, Maurstad Ola. Well-to-wheel study of passenger vehicles in the Norwegian energy system. Energy 2007;32(4):437–45. https://doi.org/10.1016/j.energy.2006.07.029. 4, http://linkinghub.elsevier.com/retrieve/pii/S0360544206001939. ISSN 03605442.
[9] Campanari Stefano, Manzolini Giampaolo, Garcia de la Iglesia Fernando. Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. J Power Sources 2009;186(2):464–77. https://doi.org/10.1016/j.jpowsour.2008.09.115. 1, http://linkinghub.elsevier.com/retrieve/pii/S0378775308018934. ISSN 03787753.
[10] Torchio Marco F, Santarelli Massimo G. Energy, environmental and economic comparison of different powertrain/fuel options using well-to-wheels assessment, energy and external costs - european market analysis. Energy 2010;35(10):4156–71. https://doi.org/10.1016/j.energy.2010.06.037. ISSN 03605442.
[11] Sharma Ashish, Strezov Vladimir. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. Energy 2017;133:1132–41. https://doi.org/10.1016/j.energy.2017.04.160. 8, http://linkinghub.elsevier.com/retrieve/pii/S0360544217307375. ISSN 03605442.
[12] Zhou Boya, Wu Ye, Zhou Bin, Wang Renjie, Ke Wenwei, Zhang Shaojun, Hao Jiming. Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. Energy 2 2016;96:603–13. https://doi.org/10.1016/j.energy.2015.12.041. http://linkinghub.elsevier.com/retrieve/pii/S0360544215016837. ISSN 03605442.
[13] Bicer Yusuf, Dincer Ibrahim. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour Conserv Recycl 2018;132:141–57. https://doi.org/10.1016/j.resconrec.2018.01.036. 5, http://linkinghub.elsevier.com/retrieve/pii/S0921344918300363. ISSN 09213449.
[14] Xylia Maria, Leduc Sylvain, Laurent Achille-B, Patrizio Piera, van der Meer Yvonne, Kraxner Florian, Silveira Semida. Impact of bus electrification on carbon emissions: the case of Stockholm. J Clean Prod 2019;209:74–87. https://doi.org/10.1016/J.JCLEPRO.2018.10.085. 2, https://www.sciencedirect.com/science/article/pii/S0959652618330993. ISSN 0959-6526.
[15] Burchart-Korol Dorota, Jursova Simona, Fole,ga Piotr, Korol Jerzy, Pustejovska Pavlina, Blaut Agata. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. J Clean Prod 2018;202:476–87. https://doi.org/10.1016/J.JCLEPRO.2018.08.145. 11, https://www.sciencedirect.com/science/article/pii/S0959652618325009?via%3Dihub. ISSN 0959-6526.
[16] Faria Ricardo, Marques Pedro, Moura Pedro, Freire Fausto, Delgado Joaquim, Aníbal T, de Almeida. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sustain Energy Rev 2013;24:271–87. https://doi.org/10.1016/J.RSER.2013.03.063. 8, https://www.sciencedirect.com/science/article/pii/S1364032113002220. ISSN 1364-0321.
[17] García Sánchez Juan Antonio, López Martínez José María, Lumbreras Martín Julio, Flores Holgado María Nuria, Morales Hansel Aguilar. Impact of Spanish electricity mix, over the period 2008-2030, on the life cycle energy consumption and GHG emissions of electric, hybrid diesel-electric, fuel cell hybrid and diesel bus of the madrid transportation system. Energy Convers Manag 2013;74(7):332–43. https://doi.org/10.1016/j.enconman.2013.05.023. 10, http://linkinghub.elsevier.com/retrieve/pii/S0196890409000764Ωhttp://linkinghub.elsevier.com/retrieve/pii/S0196890413002835. ISSN 01968904.
[18] Francisco Choma Ernani, Maria Lie Ugaya Cássia. Environmental impact assessment of increasing electric vehicles in the Brazilian fleet. J Clean Prod 2017;152:497–507. https://doi.org/10.1016/J.JCLEPRO.2015.07.091. 5, https://www.sciencedirect.com/science/article/pii/S0959652615010203. ISSN 0959-6526.
[19] Correa G, Muñoz P, Falaguerra T, Rodriguez CR. Performance comparison of conventional, hybrid, hydrogen and electric urban buses using well to wheel analysis. Energy 2017;141. https://doi.org/10.1016/j.energy.2017.09.066. ISSN 03605442.
[20] Wang Michael. Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts. J Power Sources 2002;112(1):307–21. https://doi.org/10.1016/S0378-7753(02)00447-0. ISSN 03787753.
[21] Sam Sprik, Kurtz Jennifer, Saur Genevieve, Onorato Shaun, Ruple Matt, Ainscough Chris. Next generation hydrogen station composite data products: retail stations, data through quarter 4 of 2017. Technical report. 2017. https://www.nrel.gov/docs/fy18osti/71645.pdf.
[22] Eudy L, Post M. BC Transit fuel cell bus project evaluation results: second report. Technical report. 2014. https://www.nrel.gov/docs/fy14osti/62317.pdf.
[23] Lajunen Antti. Lifecycle costs and charging requirements of electric buses with different charging methods. J Clean Prod 2018;172:56–67. https://doi.org/10.1016/J.JCLEPRO.2017.10.066. 1, https://www.sciencedirect.com/science/article/pii/S0959652617323594?via%3Dihub. ISSN 0959-6526.
[24] Chen Zhibin, Yin Yafeng, Song Ziqi. A cost-competitiveness analysis of charging infrastructure for electric bus operations. Transp Res C Emerg Technol 2018;93:351–66. https://doi.org/10.1016/J.TRC.2018.06.006. 8, https://www.sciencedirect.com/science/article/pii/S0968090X18308465#s0060. ISSN 0968-090X.
[25] G. (Gianfranco) Pistoia. Lithium-ion batteries : advances and applications. ISBN 9780444595133.
[26] Mahmoud Moataz, Garnett Ryan, Ferguson Mark, Kanaroglou Pavlos. Electric buses: a review of alternative powertrains. Renew Sustain Energy Rev 2016;62:673–84. https://doi.org/10.1016/j.rser.2016.05.019. ISSN 13640321.
[27] Rupp Matthias, Handschuh Nils, Rieke Christian, Kuperjans Isabel. Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: a case study of electric buses in Germany. Appl Energy 2019;237:618–34. https://doi.org/10.1016/J.APENERGY.2019.01.059. 3, https://www.sciencedirect.com/science/article/pii/S0306261919300595. ISSN 0306-2619.
[28] Worldbank. Electric power transmission and distribution losses (% of output) — Data. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.
[29] Informes, CAMMESA Descargas de. http://portalweb.cammesa.com/memnet1/Pages/descargas.aspx.
[30] Sbroiavacca Nicolás Di, Nadal Gustavo, Lallana Francisco, James Falzon, Calvin Katherine. Emissions reduction scenarios in the argentinean energy sector. Energy Econ 2016;56:552–63. https://doi.org/10.1016/j.eneco.2015.03.021. ISSN 01409883.
[31] Ministerio de Planificación federal inversión pública y servicios) cameron, daniel (secretaría de Energía. Resolución Nº 1125/2013. Secretaría de Energía, Ministerio de Planificación Federal, Inversión Pública y Servicios.; 2013. http://servicios.infoleg.gob.ar/infolegInternet/anexos/220000-224999/224799/norma.htm.
[32] Ambat Indu, Srivastava Varsha, Sillanpää Mika. Recent advancement in biodiesel production methodologies using various feedstock: a review. Renew Sustain Energy Rev 2018;90:356–69. https://doi.org/10.1016/J.RSER.2018.03.069. 7, https://www.sciencedirect.com/science/article/pii/S1364032118301588#s0040. ISSN 1364-0321.
[33] Talebian-Kiakalaieh Amin, Saidina Amin Nor Aishah, Mazaheri Hossein. A review on novel processes of biodiesel production from waste cooking oil. Appl Energy 2013;104:683–710. https://doi.org/10.1016/J.APENERGY.2012.11.061. 4, https://www.sciencedirect.com/science/article/pii/S0306261912008665#b0145. ISSN 0306-2619.
[34] e Energia Minas. http://www.mme.gov.br/web/guest/secretarias/energia-eletrica/publicacoes/boletim-de-monitoramento-do-sistema-eletrico/boletins-2018.
[35] Cristina Claudia, Moore Sanchez, Rego Erik Eduardo, Kulay Luiz. The Brazilian electricity supply for 2030: a projection based on economic. Environ Tech Criteria 2017;7(4):17–29. https://doi.org/10.5539/enrr.v7n4p17.
[36] Raimundo Danielle Rodrigues, dos Santos Ivan Felipe Silva, Filho Geraldo Lúcio Tiago, Barros Regina Mambeli. Evaluation of greenhouse gas emissions avoided by wind generation in the Brazilian energetic matrix: a retroactive analysis and future potential. Resour Conserv Recycl 2018;137:270–80. https://doi.org/10.1016/J.RESCONREC.2018.06.020. 10, https://www.sciencedirect.com/science/article/pii/S0921344918302404. ISSN 0921-3449.
[37] Diário oficial da União. http://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=24/03/2016&jornal=1&pagina=1&totalArquivos=112; 2016.
[38] Cremonez Paulo André, Feroldi Michael, Nadaleti Willian Cézar, de Rossi Eduardo, Feiden Armin, Pasuch de Camargo Mariele, Cremonez Filipe Eliazar, Fernandes Klajn Felipe. Biodiesel production in Brazil: current scenario and perspectives. Renew Sustain Energy Rev 2015;42:415–28. https://doi.org/10.1016/j.rser.2014.10.004. 2, http://linkinghub.elsevier.com/retrieve/pii/S1364032114008211. ISSN 13640321.
[39] Hotza D, Diniz da Costa JC. Fuel cells development and hydrogen production from renewable resources in Brazil. Int J Hydrogen Energy 2008;33(19):4915–35. https://doi.org/10.1016/J.IJHYDENE.2008.06.028. 10, https://www.sciencedirect.com/science/article/pii/S0360319908007428. ISSN 0360-3199.
[40] Reportes — energía abierta — comisión nacional de Energía. http://energiaabierta.cl/reportes/.
[41] Gómez Carla Rúa, Arango-Aramburo Santiago, Larsen Erik R. Construction of a Chilean energy matrix portraying energy source substitution: a system dynamics approach. J Clean Prod 2017;162:903–13. https://doi.org/10.1016/j.jclepro.2017.06.111. ISSN 09596526.
[42] Bezerra B, Mocarquer S, Barroso L, Rudnick H. Expansion pressure: energy challenges in Brazil and Chile. IEEE Power Energy Mag 2012;10(3):48–58. https://doi.org/10.1109/MPE.2012.2188665. 5, http://ieeexplore.ieee.org/document/6185787/. ISSN 1540-7977.
[43] DTO-11 09-May-2008 MInisterio de economía. Fomento Y Reconstrucción, subsecretaria de economia, fomento y econstruccion - ley Chile - biblioteca del Congreso Nacional. https://www.leychile.cl/Navegar?idNorma=271031.
[44] Producing ammonia and fertilizers: new opportunities from renewables.

https://www.iea.org/media/news/2017/Fertilizer_manufacturing_Renewables_01102017.pdf.
[45] Markel T, Brooker A, Hendricks T, Johnson V, Kelly K, Kramer B, O'Keefe M, Sprik S, Wipke K. ADVISOR: a systems analysis tool for advanced vehicle modeling. J Power Sources 2002;110(2):255–66. https://doi.org/10.1016/S0378-7753(02)00189-1. 8, http://linkinghub.elsevier.com/retrieve/pii/S0378775302001891. ISSN 03787753.
[46] Correa G, Santarelli M, Borello F, Cestino E, Romeo G. Flight test validation of the dynamic model of a fuel cell system for ultra-light aircraft. Proc Inst Mech Eng G J Aerosp Eng 2015a;229(5):917–32. https://doi.org/10.1177/0954410014541081. 4, http://pig.sagepub.com/lookup/doi/10.1177/0954410014541081. ISSN 0954-4100.
[47] Muñoz Pedro M, Correa Gabriel, Gaudiano Marcos E, Fernández Damián. Energy management control design for fuel cell hybrid electric vehicles using neural networks. Int J Hydrogen Energy 2017;42(48):28932–44. https://doi.org/10.1016/j.ijhydene.2017.09.169. 11, https://linkinghub.elsevier.com/retrieve/pii/S0360319917338855. ISSN 03603199.
[48] Bubna Piyush, Brunner Doug, Gangloff John J, Advani Suresh G, Prasad Ajay K. Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications. J Power Sources 2010;195(12):3939–49. https://doi.org/10.1016/j.jpowsour.2009.12.080. ISSN 03787753.
[49] de Miranda PEV, Carreira ES, Icardi UA, Nunes GS. Brazilian hybrid electric-hydrogen fuel cell bus: improved on-board energy management system. Int J Hydrogen Energy 2017;42(19):13949–59. https://doi.org/10.1016/J.IJHYDENE.2016.12.155. 5, https://www.sciencedirect.com/science/article/pii/S0360319917300216#fig6. ISSN 0360-3199.
[50] Gao Dawei, Jin Zhenhua, Zhang Junzhi, Li Jianqiu, Ouyang Minggao. Development and performance analysis of a hybrid fuel cell/battery bus with an axle integrated electric motor drive system. Int J Hydrogen Energy 2016;41(2):1161–9. https://doi.org/10.1016/J.IJHYDENE.2015.10.046. 1, https://www.sciencedirect.com/science/article/pii/S0360319915302962#fig11. ISSN 0360-3199.
[51] Correa G, Borello F, Santarelli M. Sensitivity analysis of temperature uncertainty in an aircraft PEM fuel cell. Int J Hydrogen Energy 2011;36(22):14745–58. https://doi.org/10.1016/j.ijhydene.2011.08.036. ISSN 03603199.
[52] Correa G, Borello F, Santarelli M. Sensitivity analysis of stack power uncertainty in a PEMFC-based powertrain for aircraft application. Int J Hydrogen Energy 2015b;40(32):10354–65. https://doi.org/10.1016/j.ijhydene.2015.05.133. 8 ISSN 03603199.
[53] Simmons Kyle, Guezennec Yann, Onori Simona. Modeling and energy management control design for a fuel cell hybrid passenger bus. J Power Sources 2014. https://doi.org/10.1016/j.jpowsour.2013.08.019. ISSN 03787753.
[54] Du Jiuyu, Li Feiqiang, Li Jianqiu, Wu Xiaogang, Song Ziyou, Zou Yunfei, Ouyang Minggao. Evaluating the technological evolution of battery electric buses: China as a case. Energy 2019;176:309–19. https://doi.org/10.1016/J.ENERGY.2019.03.084. 6, https://www.sciencedirect.com/science/article/pii/S0360544219304888. ISSN 0360-5442.
[55] Han Hao, Cheng Xiang, Liu Zongwei, Zhao Fuquan. China's traction battery technology roadmap: targets, impacts and concerns. Energy Policy 2017;108:355–8. https://doi.org/10.1016/J.ENPOL.2017.06.011. 9, https://www.sciencedirect.com/science/article/pii/S0301421517303658. ISSN 0301-4215.
[56] Karabasoglu Orkun, Michalek Jeremy. Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy Policy 2013;60:445–61. https://doi.org/10.1016/j.enpol.2013.03.047. 9, http://linkinghub.elsevier.com/retrieve/pii/S0301421513002255. ISSN 03014215.
[57] Mahlia TMI, Tohno S, Tezuka T. A review on fuel economy test procedure for automobiles: implementation possibilities in Malaysia and lessons for other countries. Renew Sustain Energy Rev 2012;16(6):4029–46. https://doi.org/10.1016/j.rser.2012.03.032. ISSN 13640321.
[58] Diego-Ayala Ulises. An investigation into hybrid power trains for vehicles with regenerative braking. Mech Eng 2007;240(February):240.
[59] Wang Guangjin, Yi Yu, Liu Hai, Gong Chunli, Wen Sheng, Wang Xiaohua, Tu Zhengkai. Progress on design and development of polymer electrolyte membrane fuel cell systems for vehicle applications: a review. Fuel Process Technol 2018. https://doi.org/10.1016/j.fuproc.2018.06.013. ISSN 03783820.
[60] Cano Zachary P, Banham Dustin, Ye Siyu. Andreas hintennach, jun Lu, michael fowler, and zhongwei chen. Batteries and fuel cells for emerging electric vehicle markets. Nat Energy 2018;3(4):279–89. https://doi.org/10.1038/s41560-018-0108-1. ISSN 20587546.
[61] U.S. Department of Energy (DOE). DOE technical targets for fuel cell systems and stacks for transportation applications. https://www.energy.gov/eere/fuelcells/doe-technical-targets-fuel-cell-systems-and-stacks-transportation-applications.
[62] Rosa Aldo da, Rosa Aldo da. Hydrogen storage. Fund Renew Energy Process 2013;429–482. https://doi.org/10.1016/B978-0-12-397219-4.00011-4. 1, https://www.sciencedirect.com/science/article/pii/B9780123972194000114.
[63] Hacatoglu Kevork, Dincer Ibrahim, Rosen Marc A. Sustainability of a wind-hydrogen energy system: assessment using a novel index and comparison to a conventional gas-fired system. Int J Hydrogen Energy 2016;41(19):8376–85. https://doi.org/10.1016/j.ijhydene.2016.01.135. 5, http://linkinghub.elsevier.com/retrieve/pii/S0360319916002123. ISSN 03603199.
[64] Hacatoglu Kevork. A systems approach to assessing the sustainability of hybrid community energy systems by. 2014. PhD thesis.