Energy 141 (2017) 537–549

Contents lists available at ScienceDirect

Energy

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

Performance comparison of conventional, hybrid, hydrogen and electric urban buses using well to wheel analysis

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ARTICLE INFO

Article history:
Received 16 May 2017
Received in revised form
22 August 2017
Accepted 16 September 2017
Available online 20 September 2017

Keywords:
Well to wheel analysis
Dynamic vehicle model
Electric
Diesel and hybrid buses
Hydrogen
Diesel
Battery

ABSTRACT

This work presents a new method to compare energy and environmental performances of five types of urban passenger buses powertrains using a multiphysic index on the basis of a well to wheel analysis. The well to tank step was made for present and future (year 2030) scenarios using different assumptions for the years to come and obtaining various energy and environmental parameters. Additionally, the tank to wheel analysis was performed using dynamic models of vehicles, two different driving cycles and four ranges. Later both stages were integrated in a well to wheel stage where relevant indexes were proposed and discussed. In order to properly asses the different hypotheses for systems, range, cycles and scenarios; a multiphysics indicator (Integrated Sustainability Index), valued between zero and one was used. The best results were achieved by hybrid electric vehicles for short and medium terms. In the long term battery electric vehicles are convenient only for short driving range, while the fuel cell buses yield good performances for more extended driving ranges. For the cleaner powertrains to be competitive, hydrogen production must be fed with clean and renewable energies and the renewable energy share in the electric energy matrix should be considerably high.

1. Introduction

Worldwide, 18 million barrels of oil each day are consumed in vehicular traffic [1]. Our vehicles emit 2.7 billion tons of dioxide each year [2], nevertheless in recent years, in end-use sectors, the transport sector delivered by far the largest emissions reduction, achieved by tightening fuel-economy standards. However, the share of this sector in emissions remains very high and also is one major consumer of fossil resources (In 2013 accounted for 63.8% of world oil consumption [2]), being one of the biggest contributors to the global consumption of energy. The employment of innovative powertrains such as full BEV (Battery Electric Vehicles); Hydrogen enriched Compressed Natural Gas (HCNG) powered vehicles; Fuel Cell Hybrid Electric Vehicles (FCHEV) and Hybrid Electrics Vehicles (HEV) seems a very promising step towards the energy reduction, global and local environment protection and more sustainable economic growth [3].

At present, in the transport sector, internal combustion engine (ICE) vehicles are the headlines, but it is inevitable that a new technology will eventually replace them and everything seems to indicate that the technology will be electric vehicles [4]. The interest in electric vehicles has increased rapidly over the past few years. New registrations of electric cars (including both battery electric and plug-in hybrids) increased by 70% between 2014 and 2015, with over 550.000 vehicles being sold worldwide in 2015 [2]. Fuel cell buses and battery electric buses have some key advantages over ICE vehicle as, not producing any pollutant emissions directly from their operation, noiseless and highly efficient [5]. Their emissions are entirely upstream related to production of electricity and hydrogen. This is especially advantageous in city centers where typically there is heavy traffic and the air quality can be poor [6]. Therefore, the use of fuel cells for transit reduces dependence on petroleum and adverse effects of price fluctuations. For these reasons, Fuel Cell Electric Vehicles are progressing towards commercialization and the number of FC bus and FC manufacturers are increasing steadily [7]. From a transportation service cost point of view, Lin et al. [8] studied the people's willingness to pay for the adoption of new energy buses in the four most developed cities of

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https://doi.org/10.1016/j.energy.2017.09.066
0360-5442/

Notation

Latin symbols

A	Frontal area, m^2
A_x	Concentration of emission gas in the local environment, μ g h km^{-1}
$A_{x,st}$	Ambient air quality standard for each gas emission, μ g m^{-3}
C_D	Aerodynamic drag coefficient
En	Energy, J
F	Faraday constant, C mol^{-1}
f_0	Rolling factor
g	Gravitational constant, ms^{-2}
I	Current, A
m	Mass, kg
M	Molar mass, kg mol^{-1}
N_C	Number of cells
P_{aux}	Power, W
V	Speed, ms^{-1}
W_{EI_i}	Weight of contaminant i for the emission index

Greek symbols

α	Road slope, rad
η	Efficiency
ρ	Air density, kgm^{-3}
τ	Quantity of each air contaminant by km, μ g km^{-1}
ϕ	Residence time of each air contaminant, h

Abbreviations and acronyms

aux	Auxiliaries
elec	Electronic components
mec	Mechanical components
req	Required
AUX VEH	Vehicle auxiliaries
BAT	Battery
BEV	Battery electric vehicle
CI	Compression ignition
CNG	Compressed natural gas
CT	Charging time
DC/AC	Booster buck converter
DC/DC	Inverter
DIFF	Final drive/Differential
DV	Diesel vehicle
EI	Emission index
EM	Electric motor
EV	Electric vehicle
FC	Fuel cell
FC AUX	Fuel cell auxiliaries
FCHEV	Fuel cell hybrid electric vehicle
FCS	Fuel cell system
GB	Gear box
GHG	Green house gases
H_2	Compressed gaseous hydrogen
HCNG	Hydrogen enriched compressed natural gas
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ISI	Integrated sustainability index
LCA	Life cycle analysis
LHV	Low heating value
MC	Mechanical coupling
NG	Natural gas
PEMFC	Proton exchange membrane fuel cell
PT	Powertrain
RLED	Reciprocal of linear energy density
SI	Spark ignition
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

China. The results show that approximately eighty percent of the respondents in the four cities would like to pay a higher fare to support the adoption of buses powered with renewable energies.

However there are significant technological barriers, such as the limited driving range of those vehicles and the lack of a battery and hydrogen charging infrastructure, that still prevent the widespread usage of EVs [9]. For BEVs, technical barriers are mostly associated with battery technology [10]. A significant challenge is the relatively low energy density of batteries, which means that, for a reasonable range, they have to be large, heavy and expensive. For example, with present technology a range of 200 km requires roughly 150 kg of lithium ion cells or more than 500 kg of lead acid batteries. With FCHEVs the infrastructure problem is truly a significant one [11], there is very little commercial hydrogen-refueling infrastructure in the world and it exists only in very localized areas [12]. This means that even if an individual wishes to buy a FCHEV they are prohibited from doing so due to the lack of support infrastructure [13]. On the other hand, Diesel hybrid city buses are estimated around 30–50% more expensive that conventional Diesel buses [6]. The variation can be partly explained by the different hybrid technologies [14].

When it is planned to concretely install some of these new transport technologies, the subjects discussed before shows that it is necessary a global vision with the aim to analyze the behavior of the systems under different scenarios, allowing to examine the performance of vehicles, energy consumption, range autonomy and environmental impact, when they are fed with varied energy sources and driven along different types of roads, such as the Well-to-Wheel (WTW) analysis. A WTW analysis is also called a fuel-cycle analysis in the fuels transportation field and a life-cycle analysis (LCA) for consumer products [15].

There are many studies in literature based in WTW analysis for detailed examination of the transport systems and diverse generation types applied to different countries. The WTW analysis, developed by the Argonne National Laboratory, is a useful approach for evaluating greenhouse gas emissions, among other important indicators, produced by various means of transport using fuels produced through different pathways. It takes into account all the processes from Natural Resources extraction and/or exploitation until the vehicle operation. This analysis can be broken down in two stages, well to tank (WTT) and tank to wheel (TTW). The first stage, WTT, includes the energy costs of natural resources extraction, exploitation, transportation, processing and delivery. The concept of TTW refers to the efficiency of the vehicle itself, since fuel is loaded until it is transformed into mechanical energy and heat.

Wang [15] studied the impact of a fuel cell vehicle using the GREET model, and evaluated WTW energy and emissions; Mizsey and Newson [16] compared five powertrain/fuel combinations, considering WTW efficiency, greenhouse gases (GHG) emissions and investment costs; the best efficiency was obtained for the hybrid electric vehicle (HEV) with an internal combustion engine fed with diesel, while the best WTW GHG emissions was obtained for the FCHEV, operated with compressed H_2, produced on a centralized plant. In Simmons et al. (2014) [17] a Ballard fuel cell stack was used. The model for the fuel cell used in this study is a static model which neglects dynamic behavior. The research is founded on an energy consumption analysis, which is carried out on the basis of extensive simulations in different bus routes. Five different full size hybrid and electric city bus configurations were considered in this study; two parallel and two series hybrid buses, and one electric city bus. Overall, the simulation results indicate that plug-in hybrid and electric city buses have the best potential to reduce energy consumption and emissions. Hu et al. [18] made a TTW analysis of a series plug-in hybrid electric bus characterized by the recuperation and fuel-to-traction efficiencies, which are quantified and compared for two optimization-based energy management strategies. Campanari et al. [19] presents a study of the energy and environmental balances for FCHEV and BEV through the method of WTW analysis, applied to ECE-EUDC driving cycle simulations, using efficiency maps models. Yazdanie et al. [20] presents a WTW analysis for different passenger car drivetrain technologies and energy carrier production pathways in Switzerland. Torchio and Santarelli [21] proposes a WTW global index that takes into account the energy and environmental aspects, through the assignment of the costs associated to the energy and to the pollutant emissions. In Svensson et al. [22] work, a WTW approach was applied in order to evaluate the energy and environmental impacts of introducing hydrogen in the transportation sector under conditions relevant for the Norwegian energy system. In Garcia et al. [23] examined the environmental impact caused by the life cycle of the process of production, conditioning, and transporting of the fuels used by buses (diesel, biodiesel (B100), a blended biodiesel at 20% (B20), and natural gas) is examined, where a WTW analysis was also included. Sharma & Stresof [24] performed the environmental and economic life cycle analysis of the impacts of alternative transport fuels and a comparison with conventional fuels for Australian conditions. Karabasoglu and Michalek [25] report that the driving conditions affect the performance of different powertrains producing efficiencies and GHG emissions changes, hence using significantly different driving cycles would allow a more comprehensive analysis and reduce the bias yielded by the use of a single driving cycle. In Zhou et al. study [26], three BEV models were tested on-road while participating in the demonstration project in Macao and LCA and WTW analyses were applied in the energy and environmental assessments for alternative fuel options and battery systems.

In this work, a general method to compare energy and environmental performances of different types of powertrains and energy vectors using a single multiphysic index is proposed. The study is carried out within the WTW scope and applied to an urban passenger bus with five different propulsion systems, fed with their respective fuels (or energy vectors) obtained from different sources. The transport sector is analyzed as an essential constituent part of the growth of a smart city. In turn, in the WTT stage different primary energies for the fuels and energy scenarios for the production of electricity, both current and future, are evaluated framed to Argentina. The buses energy consumption and emissions (TTW stage) vary significantly due to driving conditions (i.e. congestion, geography, and number of stops) and propulsion configurations (i.e. degree of hybridization, battery type, and fuel cell type) [27]. Therefore in the TTW stage dynamic models were used in this work along with two different driving cycles that impose different driving conditions.

In this context, all buses systems, relevant fuels, and primary energy sources were compared with the aim to answer the next questions:

- What are the alternative uses of a particular resource and how it can be used in an efficient way?
- What are the alternative ways to produce a given energy vector and which of these can keep the best prospects?

2. Methods

The method used is based on the description of individual discrete processes, which are steps or complete relevant pathways for the selection of energy and emissions data. This process was carried out considering the energy point of view and harmful emissions to the environment.

For the WTT analysis two scenarios for the production of energy vectors in Argentina were proposed, the current one (year 2018) for all the energy vectors and a future scenario (year 2030) for electricity generation, based on the work of Di Sbroiavacca et al. [28], and hydrogen production. In both cases Diesel, Compressed Gaseous Hydrogen (H_2), hydrogen enriched compressed natural gas (HCNG) and Electricity were considered as the output energy vectors.

Fig. 1, shows the primary energy sources, the transport and distribution process, and the relevant fuels and energy vectors to supply all propulsion systems used, giving a visual description of the pathways.

For the Diesel, the emissions and primary energies needed to produce it from crude oil were considered along with its distribution by truck and barges.

The H_2 was obtained from natural gas reforming and transported by virtual pipelines, for the current scenario and electrolytic hydrogen from wind farms delivered through pipelines for a future scenario.

The HCNG was obtained as a mixture of the Compressed Gaseous Hydrogen and Compressed Natural Gas (CNG). The latter was considered as the U.S.A. CNG produced using the Argentinian Electric Matrix.

For the Electricity production and distribution the Argentinian electricity matrix was taken into account as a case study considering all the available generating methods in Argentina in its proper share: thermal (stem and gas turbine, diesel engine, combined cycle), nuclear, renewables (solar and wind) and hydraulic. The electricity production needs as inputs natural and enriched uranium, renewable sources such as solar and wind, and fossil fuels produced domestically and imported such as oil, gas and coal. Also the use of biofuels was considered since they are promoted by Law 26.093 ″Regulation and Promotion Regime for the Production and Sustainable Use of Biofuels", to make blends with biodiesel.

In the TTW stage five powertrains, that use the energy vectors analyzed in the WTT stage, were proposed for the usage in a bus for urban passenger transport:

- Internal Combustion Engines (ICE) fed with Diesel.
- ICE fed with HCNG (30% V/V hydrogen on CNG).
- Fuel Cell Hybrid Electric Vehicle (FCHEV) fed with hydrogen.
- Battery Electric Vehicle (BEV) fed with electricity.
- Hybrid Electric Vehicle (HEV) fed with diesel.

These powertrains were studied on a bus for urban passenger transport for the WTW analysis from the perspective of mass transit. The main features of the bus are listed in Table 1. As shown

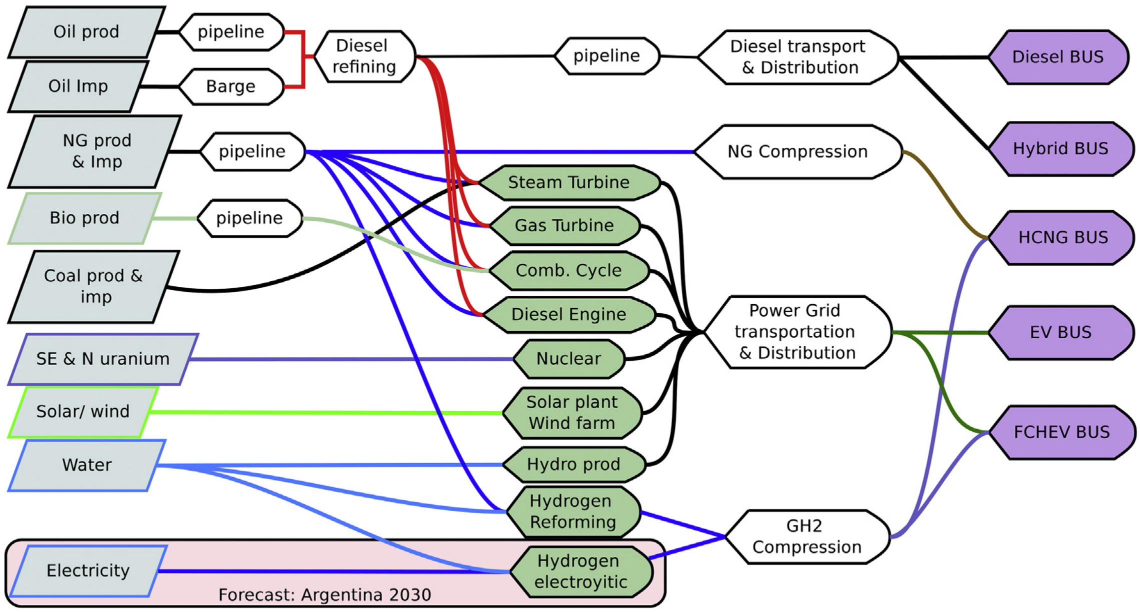

Fig. 1. Energy sources, transport and distribution process, relevant fuels and energy vectors to supply all propulsion systems used.

in Fig. 2, each model used allows to analyze the performance of buses providing a large number of output data from which only a few of them are used for the purpose of this work and are described in section 2.3.

The powertrains have been studied with four different ranges: 100 km, 200 km, 300 km and 400 km, and two driving cycles designed to assess the emission levels and fuel efficiency in vehicles: EUDClow (Extra Urban Driving Cycle for Low Powered Vehicles) [29] and UK-BUS (London Transit Bus Drive Cycle) [30]. The driving patterns affect fuel consumption significantly, as the analysis made in Karabasoglu et al. work shows [25]. Fig. 3 graphically displays the frequency of speed of the two driving cycles used in this work. UK-BUS cycle represents a real life cycles with more starts and stops that the EUDClow cycle but with less final speed, as shown in Fig. 3.

2.1. Well to tank model description

The model used is the well-known GREET [15], which is an analytical tool for estimating fuel-cycle energy use and emissions. The model was used to study the fuel-cycle energy use and emissions for four different energy vectors, Diesel, H_2, HCNG, and Electricity.

2.1.1. Hydrogen production

Steam reforming of hydrocarbons is the most economical and widely used process for the production of hydrogen [31]. Actually, approximately 90% of hydrogen generated in the world is produced from fossil fuels, mainly through steam methane reforming [32,33]. Natural gas, consisting primarily of methane, is commonly used as the main feed. Electricity is also required for the compression, storage, and dispensing of hydrogen gas. The production of H_2 for the present scenario was considered from natural gas reforming with sources from the Argentinian mix of primary energies.

Currently in Argentina, H_2 is produced following the world trend of steam reforming of hydrocarbons. Since almost all the production is captive, new methods can be proposed for a future scenario. Therefore, for the future scenario its assumed that the hydrogen will be produced by wind powered electrolysis and transported via pipelines (Forecast: Argentina 2030).

Table 1
Bus parameters.

Parameter	Value	Unit
Bodywork weight	12754.4	kg
Aerodynamic drag coefficient	0.79	–
Rolling factor	0.0094	–
Wheel Radio	0.486	m
Passengers load	1500	kg

2.1.2. Electricity generation

Table 2 shows the mix of technologies, efficiencies and participation rates in the electricity generation from Argentinian mix of primary energies for the current scenario [34] including the targets to achieve by 2018 of 8% (already tendered) share of renewable energy proposed by the Argentine Republic Ministry of Energy and Mining; and the proposed scenario for the year 2030.

Each technology used for power generation from fossil sources account with different raw materials: in the case of the combined cycle, it has 88.42% of natural gas (NG) and 11.58% of gas oil; the nuclear has 68.31% of Slightly Enriched Uranium and 31.69% of Natural Uranium; the simple cycle gas turbine has 91.18% of NG and 8.82% of gas oil and finally the steam turbine has 16.06% of carbon, 59.1% of fuel oil and 24.84% of NG. The Argentinian mix of primary energies for 2030 scenarios were taken from the work Di Sbroiavacca et al. [28].

In both scenarios, the losses due to electricity distribution and transportation in the grid were taken into account.

2.1.3. Diesel production

The Diesel fuel pathways, were based on the updated inputs of Argentina and included fuel oil imported transported in barge, shale oil and traditional oil from domestic reserves, crude oil transportation, diesel refining, diesel transportation and distribution, and finally serving as fuel for the Diesel Vehicle and the Hybrid Electric Vehicle.

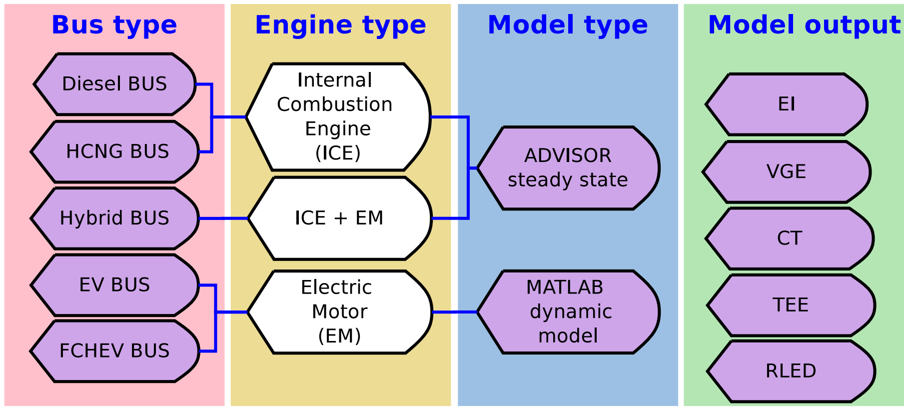

Fig. 2. TTW analysis scheme.

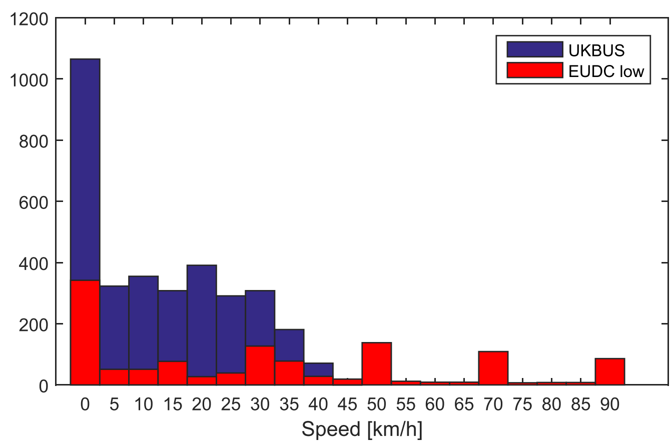

Fig. 3. Speed frequency of driving cycles.

2.1.4. *Compressed natural gas production*

The natural gas includes: extraction, processing, pipeline transport and intermediate compression. The stages considered for the feedstock of this fossil fuel are: Natural Gas import from bordering countries, shale and traditional gas from domestic reserves, electricity consumption in intermediate compression stages and natural gas transport by piping.

2.1.5. *Hydrogen enriched compressed natural gas production*

Since Argentina has an extensive fleet of CNG vehicles and a widespread CNG distribution structure, this way of H_2 utilization is considered as a natural first step for penetration as a transportation fuel [35]. Thus Compressed Natural Gas enriched with 30% of Hydrogen (in volume) is considered as fuel.

Table 2
Mix of technologies, efficiencies and participation rates in the electricity generation from Argentinian mix of primary energies.

	Efficiency	2018 shares	2030 shares
Hydro		25.095%	27%
Steam turbine	32.37	12.843%	8.8%
Nuclear	46.39	4.181%	10%
Combined cycle	56.54	43.235%	29.65%
Simple cycle	29.12	6.646%	4.55%
Wind		7%	15.5%
Solar		1%	4.5%

2.2. *Tank to wheel model description*

This section provides a description of the components used for each one of the urban passenger bus powertrains and the different mathematical models used to simulate them.

2.2.1. *Powertrain model*

The BEV and FCHEV were studied using models developed by the authors and the remaining Buses systems were simulated using ADVISOR [36] which approximates the continuous behavior of a vehicle through a series of discrete steps. During each step, steady state of the components was assumed. This assumption allows using efficiency maps of components derived from steady state tests in the laboratory.

This type of models, however, does not allow a detailed investigation of short-term dynamic power sources responses, which led to design new models of the propulsion system and control of the fuel cells and battery powered vehicles. Fig. 4 shows the energy flow diagram of the different proposed powertrain architectures, were H_2 is the hydrogen storage system, DC/DC are the Booster Buck Converters, DC/AC are Inverters, EM are the Electric Motors, MC is the Mechanical Coupling, GB are the Gearboxes, DIFF are the Final drives and Differentials.

To compute the energy required for the bus motion, several effects were taken into account: the effects of rolling of the wheel, the force exerted by gravity on slopes, the air resistance, the efficiency of electronic components, the efficiency of the electric motor as the drive power, the mechanical efficiency and the auxiliary energy required by the vehicle [37]. This model is useful for all kinds of vehicles by adjusting the various input parameters such as vehicle weight, rolling factors, drag coefficient, efficiency tables of electric motors, etc. equation (1) below expresses the electrical power needed to feed the electric motor in the authors bus model, considering rolling, gravity and aerodynamic effects, the electronic components, electric motor and mechanical efficiencies. The parameters values were specified in Table 1.

$$P_{req} = \frac{\left[\left(\frac{dV}{dt} + f_0 \cos(\alpha) + g \sin(\alpha)\right) m + \frac{1}{2} C_D \rho A V^2\right] V}{\eta_{elec} \eta_{EM} \eta_{mec}} + P_{aux} \quad (1)$$

The auxiliary system is considered to work at a constant power of 6 kW, which is consumed by the air conditioning systems, pumps, lights, instruments, etc; and are powered with electricity generated on board.

Table 3, shows the weights of all the systems in all the cycles used, where empty bus refers to vehicle bodywork and FCS means fuel cell system.

2.2.2. Diesel vehicle

This vehicle operates with a conventional powertrain consisting of a compression-ignition Caterpillar 3126E Diesel Engine, a Rockwell RM10-145A gearbox and a standard catalyst for compression ignition (CI) engines all of which add up to 1262 kg.

2.2.3. Hybrid electric vehicle

Hybrid vehicles make use of two or more power sources e.g. electric motors and internal combustion engines. There are several powertrain configurations available for vehicles such as series, parallel, series parallel, etc. For the hybrid bus a parallel configuration is adopted (see Fig. 4). The engine is a Mercedes OM611 reaching 92 kW at 4200 rpm connected to a Rockwell RM10-145A gearbox with a standard catalyst for CI engine. The electric propulsion comprises 100 modules of 6 Ah Saft Lithium Ion batteries and a 100 kW electric motor. The powertrain elements listed above weight 895 kg.

2.2.4. Hydrogen enriched compressed natural gas fueled vehicle

Argentina has a very developed infrastructure for CNG, since in the transport sector a fleet of nearby 2 million vehicles is feed with this fuel. The very wide net of pipes and service stations implies a big opportunity for implementing a future Hydrogen economy in the country [38]. The HCNG bus uses a modified Daewoo (186 kW) SI Engine which operates on a 30% hydrogen and 70% natural gas volume mixture. The engine was tested on a dynamometer bench to obtain the fuel economy and emissions maps [39]. The powertrain is completed with an Eaton Fuller RTLO-12610B gearbox and a standard catalyst for spark ignition (SI) engines adding up to 1269 kg.

2.2.5. Battery electric vehicle

These vehicles are powered by electricity stored in Li-ion batteries, especially designed for this type of vehicles. Since the power source is electricity, TTW emissions are zero. The emissions in the electricity generation process are considered in the WTT stage. Among the many advantages of electric vehicles is that of having regenerative brakes. In traditional, friction-based brake systems, the kinetic energy of the vehicle is lost as heat. Regenerative brakes allow a significant fraction of the vehicle's kinetic energy to be transformed in electrical energy and store it in the batteries as electrochemical energy. On the other hand, when a car stops at a traffic light, there is simply no fuel consumption. This contrasts with internal combustion vehicles, where fuel is consumed even when the vehicle is idle. The model used for the batteries, previously validated and published in Ref. [37], includes the effect of temperature in voltage and current using a lumped thermal model for heat generation and dissipation. The model is semi-empiric and quasi-static using experimental results of a new battery, without considering the aging of the battery. Within the model, the code defines a surface of working points of the battery using the experimental data and matches the required power with an appropriate voltage and current output or input during the simulations. Fig. 5 shows the workflow of the battery model.

As inputs the model needs the ambient temperature, the power required by the vehicle to complete the driving cycle and the power delivered by the regenerative brake of the vehicle, giving as output the voltage and current delivered, the heat transferred to the atmosphere, the battery temperature, the state of discharge and the losses due to the processes of charging and discharging.

The batteries cells connection can be in series or parallel depending the goals. Using batteries in series it is possible to increase the voltage bus maintaining the capacity of the batteries stack equal to the capacity of a single battery, while a parallel arrange increases the capacity and keeps the voltage bus of the batteries stack equal to the voltage of a single battery. Thus a stack of 56 Li-ion battery cells in series is defined as the target voltage bus, and the number of stacks in parallel varies as the bus range is increased.

Table 4 shows the parameters used in the model of battery.

2.2.6. Fuel cell hybrid electric vehicle

The powertrain architecture of the hybrid fuel cell vehicle consist of a fuel cell system with a li-ion battery. The main source of energy is hydrogen stored in a pressure vessel (350 bar) which is transformed into electricity in the fuel cell (FC Stack), with a lithium-ion battery (see model in Section 2.2.5) to help in moments in which it does not achieves to generate the required power, which can be due to delays in the response of the fuel cell or a power request that exceeds the FC maximum power. Battery charging was also considered through regenerative braking.

The Ballard FCvelocity-HD6, specifically designed for electric drive buses, delivers 150 kW (2 stack of 75 kW) of gross power with a system weight of 400 kg. The system includes air humidification, H_2 recirculation and condenser for water management [7]. Table 5 shows the main characteristics of this FC and the number of batteries used for the EUDC and for the UK cycles.

The PEMFC stack dynamic model was extracted from the work of Correa et al. [40,41] and modified by introducing appropriate parameters [42]. This model takes into account the main electrochemical, fluid-dynamic and thermal phenomena to predict the power output and it is coupled with the balance of plant model

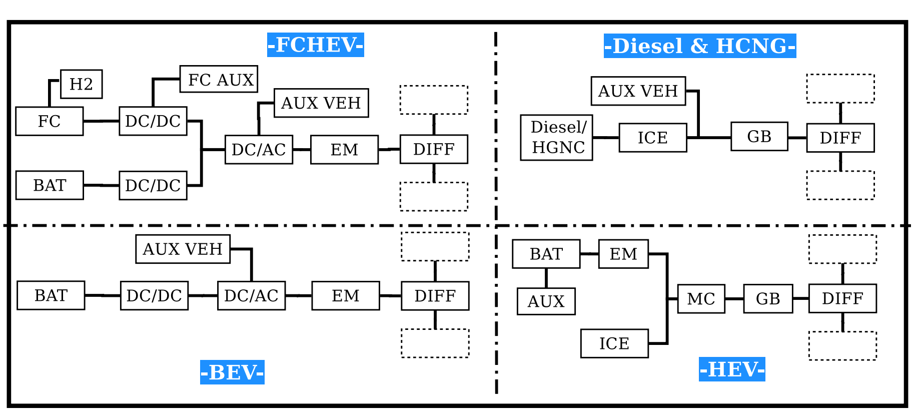

Fig. 4. Energy flow of powertrain architectures.

Table 3
Weights of all the systems in all the cycles in kg.

Range [km]	Cycle	BUS weight		FCHEV bus				BEV bus		HCNG bus		
		Empty bus	Cargo	FCS/EM	BAT	H_2 tank	Total	BAT weight	Total	PT	HCNG tank	Total
100	UK	12754	1500	750	108	209	15621	1404	15659	890	253	15658
100	EUDC	12754	1500	1000	385	166	16105	1138	15393	890	219	15624
200	UK	12754	1500	750	108	420	15832	2988	17242	890	657	16062
200	EUDC	12754	1500	1000	385	329	16268	2338	16592	890	410	15815
300	UK	12754	1500	750	108	638	16051	4854	19109	890	960	16365
300	EUDC	12754	1500	1000	385	497	16436	3662	17916	890	615	16020
400	UK	12754	1500	750	108	864	16277	7143	21397	890	1314	16719
400	EUDC	12754	1500	1000	385	665	16603	5145	19399	890	876	16281

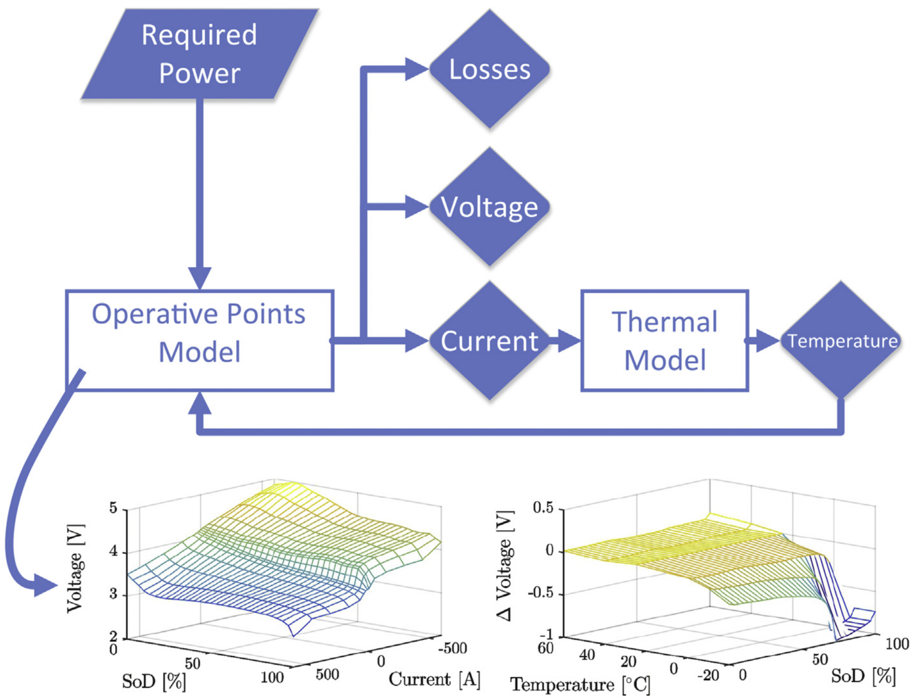

Fig. 5. Battery model scheme.

which includes compressor, cooling devices, and water management systems. In order to obtain the stack power output, the temperature of the whole system is computed (stack FC and water management system) and the input of the code needs data of the external environment (ambient temperature and pressure), the test drive profiles (altitude and speed). Moreover, since the voltage depends on the reactant pressures at the catalyst layer, the concentration needs to be described as a function of the cells operating condition.

The total consumption of hydrogen (m_{H_2}) is given by:

$$m_{H_2} = \int_{t_0}^{t_f} \frac{M_{H_2}}{N_C} 2F(I_{FC}(t) + I_{aux}(t))\, dt \qquad (2)$$

where M_{H_2} is the molar mass of hydrogen, N_C is the number of cells, I_{FC} is the stack current, I_{aux} is the auxiliaries current, F is the Faraday constant (96485 C/mol).

2.3. Relevant indexes

In order to compare the behavior of the five types of vehicles studied, indicators of different nature were selected, because of their importance in the multiphysical (energy and environmental) performance of these vehicles, for the two driving cycles described above. The indexes proposed are listed on Table 6.

Table 4
Parameters used in the battery model.

Parameter	Value	Unit
Battery Capacity	5	A h
Nominal Voltage	3.7	V
Max. Discharge Current	600	A
Max. Charge Current	30	A
Cut-off voltage	2.7	V
Number of cells	56	
Depth of discharge	70%	
Initial SOD	10%	
Maximum SOD	80%	
Minimum SOD[a]	10%	

[a] Minimum SOD at which the regenerative brake and FC are allowed to charge the battery.

2.3.1. Vehicle gravimetric energy density

This analysis goes beyond fuel efficiency and consider the

Table 5
FCS parameters.

Parameter	EUDC	UK
Number of Stacks	2	1
Active Cell Area	419	419
Stack cells no.	370	370
Gross power [k W]	150	75
H_2 purge percentage	8%	8%

gravimetric density of energy (stored energy per unit mass) as an efficiency indicator, in order to measure the amount of energy that the vehicle stores as a whole per unit of the powertrain mass. In this way a holistic perspective of it is obtained.

2.3.2. Charging time

Another important feature to make a correct comparison between mobility systems is the recharge time of storage systems, according to their autonomy range. In general, these factors are the key barrier that reduces the attractiveness of electric mobility in many contexts of choice. Range anxiety is a relatively new phenomenon in car development [43] related to the inadequacy of the electric range for daily travel activities and tries to point out the problem that electric vehicles manufactures has to overcome to compete with gasoline and diesel vehicles [44]. For a modern EV the autonomy range run between 100 km and 500 km usually, while, the refueling time for an EV, ranging from 30 min to 10 h or more [45], depending on vehicle application (Overnight or Opportunity BEV [46]). Hybrid vehicles provide an overall autonomy range similar to diesel buses and the parallel hybrid used in the Mahmoud et al. work [46] provides an additional all electric range of 10 km. With 350 or 700 bar H_2 storage, the FCHEV provides a full electric autonomy range similar to diesel bus [47].

2.3.3. Total energy efficiency

Three different energy efficiencies can be calculated, the WTT efficiency, the TTW efficiency and the WTW efficiency. The WTT energy efficiency is the energy vector output divided by the energy consumed from the sources. The TTW energy efficiency calculates the ratio between the energy needed to move the vehicle (wheel energy) and the amount of energy supplied to the vehicle as energy vectors. The WTW energy efficiency is the ratio between the energy needed to move the vehicle and the amount of energy supplied by the energy vectors to the vehicle, plus the energy consumed to produce the energy supplied to the vehicle, i.e. the energy supplied to the vehicle divided by the WTT efficiency. Equations (3)–(5) were developed considering the fact that the vehicles are fed by, at most, two energy vectors.

$$\eta_{En_{WTT_i}} = \frac{En_i}{\sum_j En_j} \tag{3}$$

$$\eta_{En_{TTW_k}} = \frac{En_{wheel_k}}{\sum_i En_i} \tag{4}$$

$$\eta_{En_{WTW_k}} = \frac{En_{wheel_k}}{\sum_i \frac{En_i}{\eta_{En_{WTT_i}}}} \tag{5}$$

where:

- i: Energy vectors.
- j: Primary energy sources.
- k: Diesel, HEV, HCNG, FCHEV and BEV.

2.3.4. Reciprocal of linear energy density

The reciprocal of linear energy density calculates the ratio between the distance covered by the buses and the amount of energy stored in them as electricity or fuel used to complete the driving cycle. The liquid and gaseous fuels energy is computed using its low heating value (LHV).

This parameter allows us to appreciate the efficiency of the vehicle but, in contrast to the energy efficiency parameter, it takes into account the vehicle weight as the aptitude of the vehicle to cover distances and not its performance in converting energies is being evaluated.

2.3.5. Emission index

This environmental impact index addresses the effects of the road transport sector on the environment (pollutant emissions, global warming, etc.). In order to take into account environmental aspects, the pollutant emissions associated to both the production procedure (WTT) step and the final utilization of a fuel step (TTW) has been evaluated. The WTT emissions in the extraction, chemical processing and transport was computed using the Greet software and the TTW emissions with the author's models and Advisor models. The indexes were obtained following Hacatoglu et al., 2016 [48] and are defined as:

$$EI = \beta_{NOx} W_{EI_{NOx}+\beta_{CO}W_{EI_{CO}}} \tag{6}$$

$$W_{EI_{NOx}} = W_{EI_{CO}} = \frac{1}{2} \tag{7}$$

$$\beta_x = \frac{A_{x,st}}{A_x} \tag{8}$$

where $A_{x,st}$ is the ambient air quality standard for each gas emission (EPA, 2011), and A_x represents the concentration of gas emission in the local environment and is calculated as shown:

$$A_x = \phi\tau \tag{9}$$

where ϕ is the residence time and τ is the quantity of each air contaminant per km. The U.S.A. Environmental Protection Agency

Table 6
Relevant indexes.

	Index	Accounting for
1.	EI: Emission Index	Environmental aspects
2.	VGE: Vehicle Gravimetric Energy Density (kWh/kg)	Energy stored per kg of power train components
3.	CT: Charging Time (min)	Charging or refueling time of energy storage
4.	TEE: Total Energy Efficiency (valued between 0 and 1)	Efficiency in energy conversion
5.	RLED: Reciprocal of Linear Energy Density (km/kWh)	Efficiency of the vehicle to cover distances

(EPA) has identified air contaminants to be monitored as part of its national ambient air quality standards [49]. In this work only two air contaminants (NOx and CO) were considered and are shown in Table 7.

The results are expressed as linear density of emissions (g/km).

2.4. The integrated sustainability index

Seeking to address a more comprehensive approach in the assessment of the sustainability of the different buses studied here, able to include efficiency ratios, autonomy ranges and the environmental friendliness degree, an Integrated Sustainability Index (ISI) (Hacatoglu et al. [48]) is proposed. The ISI index assess his performance considering appropriate weighting factors associated with those relevant indexes (described above and used as indicators) with normalized values ranging from zero to one, where one is the best possible evaluation achievable for the buses. The value of the indicator j (Ij) is multiplied by its weighting factor (Wj). The ISI of the system is obtained as the sum of this values.

All weighting factors were taken based in the criterion of reference [50] and are shown in Table 8.

3. Results and discussion

In order to analyze the results, they will be divided into two parts TTW and WTT. While the calculations were performed for all ranges (100, 200, 300 and 400 km), the figures used in this section show the performance of the five bus configurations in the lowest and highest ranges (100 and 400 km) for the two cycles and are plotted for each of the proposed scenarios.

In Fig. 6 the results of the TTW analysis are shown and each of the indexes explained in the previous section (TEE, CT, VGE, etc.) are graphed in bars. The emission index was not used in this figure, instead, each GHG emissions was plotted separately.

The hight of the indexes shown in the graphs is constructed by performing a canonical normalization of the results and thus are expressed on a scale of 0–1, with 1 being the best. In the case of the efficiency indexes (TEE, VGE and RLED) the higher efficiency is closer to one, in the case of CT and the environmental indexes the higher the parameters the lower its index. Thus, for the NOx and CO emissions the value of 1 is achieved when there are no emissions (FCHEV and BEV). The graph is divided into four parts. The lowest and highest ranges (100 and 400 km) for the two cycles were used to display the results variation.

For the UK100 it can be seen that the BEV has an excellent performance in almost all indexes, except in the CT that is the lowest. Then, the FCHEV has very good indexes, a little more even than the BEV since it has a high rate of energy efficiencies (TEE and RLED), but its gravimetric efficiency index (VGE) is very low. As the BEV, the FCHEV has excellent emission rates (zero emissions). In relation to the CT, the FCHEV has similar index to Diesel, HCNG and HEV. Diesel and HEV have similar rates, although HEV improves efficiency rates. Finally the HCNG has very low NOx (high index) and high CO (low index) emissions. In the case of EUDC100 the BEV stands out with low rates in VGE and CT and very high in emissions and efficiencies as in the UK100 case. The FCHEV also behaves similarly to the UK100. In contrast the buses with ICE (Diesel, HCNG and HEV) have significant differences with respect to the UK. The HEV improves the efficiency and CO emission rates significantly. The diesel improves in energy efficiencies and NOx emissions, but the VGE is reduced and the CO emissions increase. The HCNG improves on all indexes except for the VGE.

Table 7
Emission index parameters.

	τ[h]	$A_{x,st}$ [$\mu g \cdot m^{-3}$]
NOx	24	100
CO	840	10000

Table 8
Weight values involved in ISI index.

Ij	TEE	RLED	VGE	EI	CT
Wj	0.3	0.3	0.1	0.2	0.1

The UK400 presents a more balanced graph between the different configurations of buses, although again the BEV and the FCHEV appear to have the best performances. They practically do not modify their indexes from 100 to 400 km. In contrast the HEV presents an evident improvement since it substantially increases the VGE index. The diesel and HCNG also increases the VGE while maintaining the other indexes. The EUDC400 presents the most even scenario. Bus configurations with ICE improve on the VGE index with respect to the EUDC100, but decrease slightly with respect to the UK400. They also improve CO emission rates for the UK400 and EUDC100. The buses with electric motor (BEV and FCHEV) practically do not modify their indexes with respect to the cycle UK or to the range 100 km.

Figs. 7–10 show the WTW emissions (NOx and CO) and efficiencies (TEE and RLED) for each one of the bus configurations and for the 100 and 400 km ranges of each cycles in the 2018 scenario. In the case of the WTT only the efficiency and emissions indexes are evaluated since the CT and VGE are a vehicle-specific characteristic.

Fig. 7A shows the behavior of the TEE efficiency for the EUDC cycle with 100 km range in the 2018 scenario, where, in general, the buses with ICE have a superior performance for the WTT, on the other hand the electric motor buses have better performance for the TTW. In the case of FCHEV it has an average performance for WTT and TTW. In the WTW analysis, HEV and BEV show the best behaviors.

In Fig. 7B the range is changed (400 km) and behaviors similar to the EUDC100 can be seen. Fig. 7C shows the UK cycle for 100 km, where a remarkable deterioration can be seen in all the bushes using ICE. This behavior is due to the fact that the UK cycle has more stops than the EUDC cycle, therefore two things happen: ICE engines work much longer at lower rpm and hence lower efficiencies, and regenerative braking increases the performance of systems with electric motors. Fig. 7D increases the range to 400 km and similar behaviors to the UK100 can be seen.

A comparison of Reciprocal of Linear Energy Density (RLED) TTW and WTW for 100 km and EUDC cycle is shown in Fig. 8A and 400 km and EUDC cycle in Fig. 8B and 100 km and UK cycle en Fig. 8C and finally 400 km and UK cycle is shown in Fig. 8D. Fig. 8 outlines a different behavior of BEV and ICE systems: Energy required per km is strongly dependent on range for BEV, while Diesel, HEV, FCHEV and HCNG has only a slight dependency.

Fig. 9 reveals how the emissions related to the generation (WTT) of the electricity, hydrogen and HCNG energy vectors draw the WTW CO emissions performance to be the worst in vehicles that have little or no emissions at all. The NOx emissions plotted in Fig. 10 shows the opposite effect, in which the ICE high emissions outweigh the potential benefits of low emissions during the energy vector production (WTT).

Figs. 11 and 12 were performed to show the bus configurations and relevant indexes (see section 2.3) for the range of 100 and 400 km and for the two cycles analyzed. In order to display the multivariate data, the indexes were plotted in two-dimensional radar charts, which pretend to show a comparison between buses

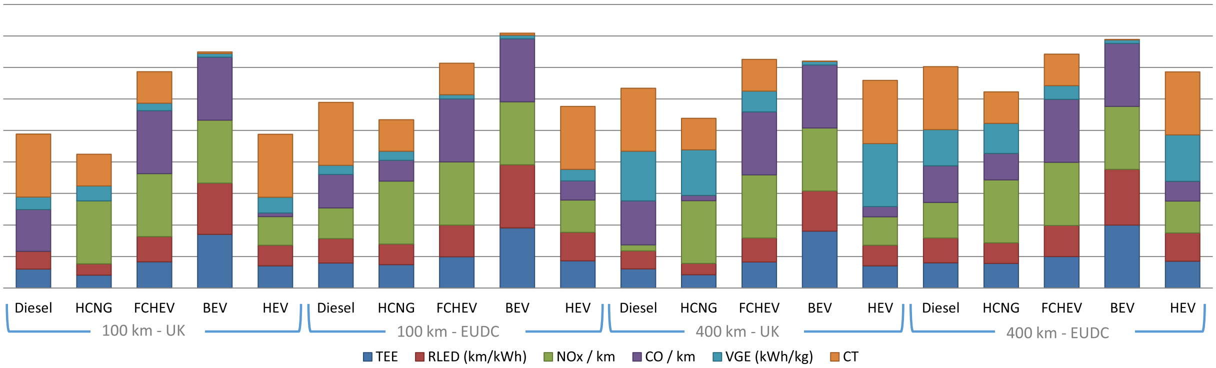

Fig. 6. TTW result, expressed on a scale of 0–1, with 1 being the best.

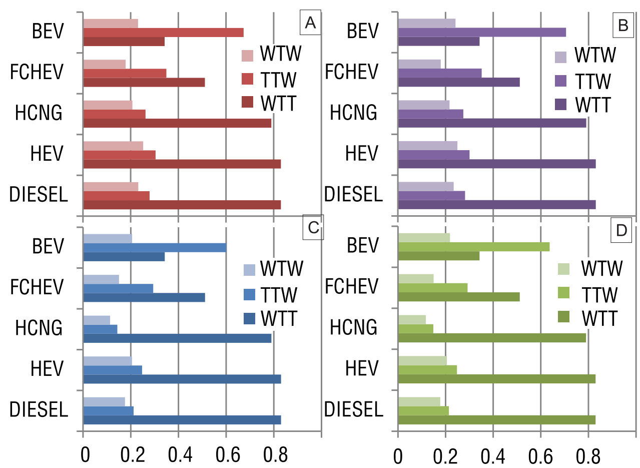

Fig. 7. WTW TEE for the EUDC cycle 2018 scenario result.

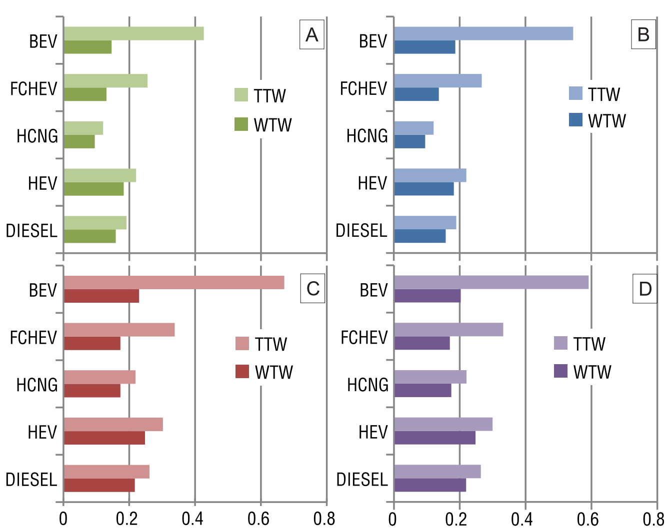

Fig. 8. RLED WTW and TTW results.

without giving any weights to the indexes used. The most desirable performance in the bus configuration occupy the periphery of the graph.

The current scenario for Argentina (2018) is shown in Fig. 11 where it can be seen that for the case of EUDC100 the HEV bus has the best behavior, except in the EI where Diesel Bus shows better performances.

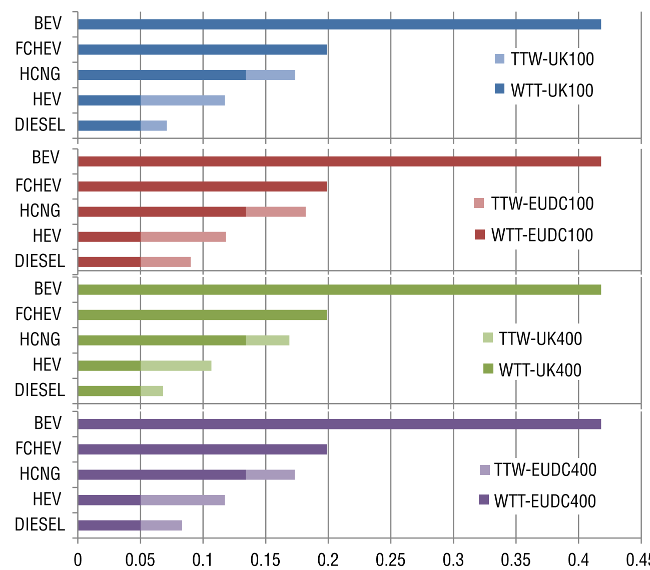

Fig. 9. WTW Emission performance - CO.

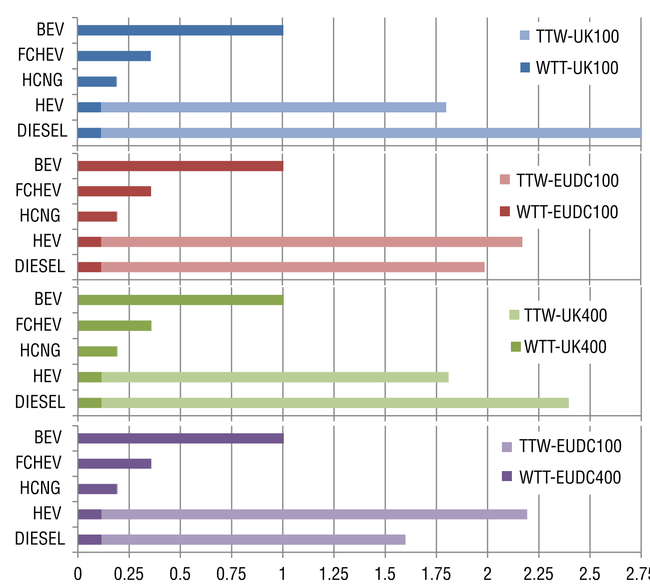

Fig. 10. WTW Emission performance - NOx.

In the 2030 scenario (Fig. 12), the electric matrix renewables participation is increased as stated in section 2.1.2 and the

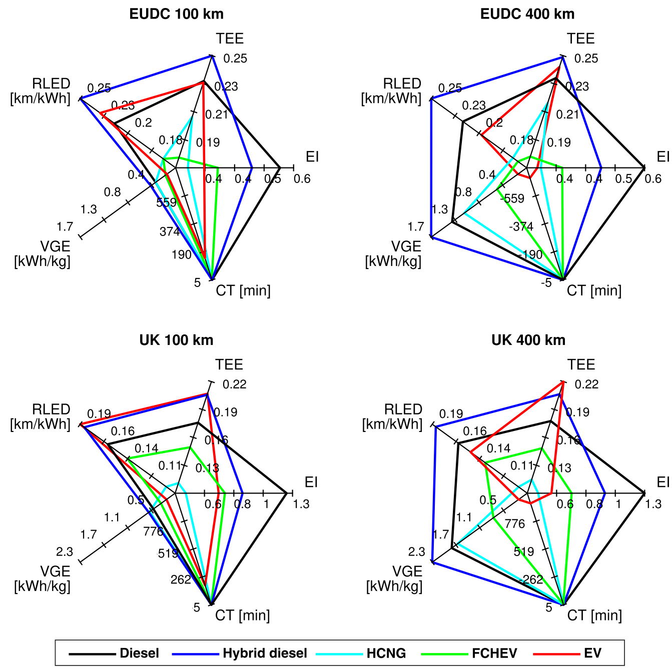

Fig. 11. Radar chart WTW 2018.

hydrogen production switched to electrolytic, through wind farms with distribution via pipeline. This conditions boost the performances of the BEV and FCHEV powertrains, attaining great efficiencies for the BEV and excellent emissions indexes for the FCHEV.

The ISI evaluations of the 2018 and 2030 scenarios for both cycles are shown in Tables 9 and 10 respectively. The cells of the table are colored in a gradient according with the values, green being the best valuation, red the worst, and white the middle point.

In Table 9 it can be seen at first glance that the ISI for HEV bus with a 400 km range is the most favorable, from the viewpoint of

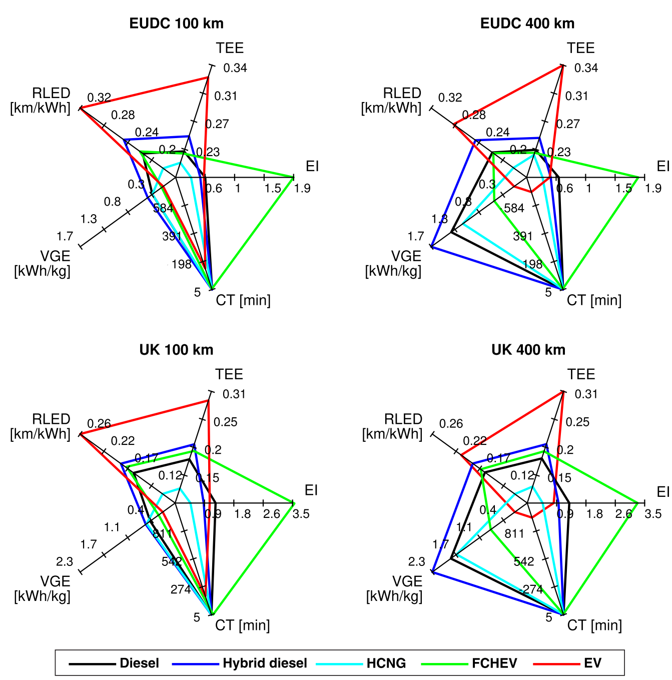

Fig. 12. Radar chart WTW 2030.

Table 9
ISI 2018.

	ISI EUDC				ISI UK			
	100	200	300	400	100	200	300	400
DIESEL	0.85	0.88	0.9	0.92	0.81	0.83	0.86	0.88
HEV	0.89	0.91	0.93	0.96	0.84	0.87	0.9	0.93
HCNG	0.63	0.66	0.67	0.69	0.45	0.47	0.48	0.5
FCHEV	0.61	0.62	0.62	0.62	0.6	0.61	0.61	0.61
BEV	0.68	0.67	0.66	0.64	0.7	0.68	0.65	0.62

Table 10
ISI 2030.

	ISI EUDC				ISI UK			
	100	200	300	400	100	200	300	400
DIESEL	0.58	0.61	0.63	0.65	0.54	0.56	0.59	0.61
HEV	0.63	0.65	0.68	0.7	0.58	0.61	0.64	0.66
HCNG	0.47	0.49	0.51	0.52	0.33	0.35	0.37	0.38
FCHEV	0.67	0.67	0.67	0.67	0.65	0.65	0.65	0.65
BEV	0.66	0.65	0.64	0.62	0.65	0.64	0.61	0.59

the range for both driving cycles, closely followed by Diesel bus. The BEV, FCHEV, and HCNG turn out to be much less favorable in every range. The BEV bus stands in the middle point for the UK cycle with a 100 km range.

As shown above BEV, FCHEV, and HCNG buses performance rely strongly on the electric matrix and the hydrogen production which for the 2018 scenario is very fossil fuel dependent. Thus their ISI performance is poor.

The 2030 scenario (Table 10), with its increase in renewable energy generation participation evens the performance of the vehicles, although it is not enough to place neither BEV nor HCNG performances over the HEV configuration. Nevertheless, with the introduction of electrolytic hydrogen from wind farms the FCHEV increase its performance, beating the HEV for UK cycle in 100 km, 200 km and 300 km ranges.

The major ISI difference between ranges is founded in BEV bus in the 2018 scenario and in the HEV bus in the 2030 scenario, while FCHEV present the most stable ISI performance in both cycles and scenarios.

In the first case, this behavior can be explained by the fact that the weight of the energy storage system increases proportionally to the range. This impacts negatively on both gravimetric (VGE) and total energy (TEE) efficiencies. In the second case, this difference is due to the change in the VGE index. In the third case, the change in the weight of the energy storage system does not increase as significantly as in the BEV in function of the range.

Comparing both cycles, it can be observed that the HCNG bus improves its performance significantly in relation to the other vehicles, as the range increases in the EUDC cycle, but not in the UK one.

4. Conclusions

In this work a new method to compare different buses powertrains using a WTW analysis is presented. This analysis was divided in two stages, WTT and TTW; framed to Argentina and performed for five different buses configurations: Diesel, Hybrid, Compressed Natural Gas enriched with Hydrogen, Proton Exchange Membrane Fuel Cell and Battery Electric Vehicles. The WTT step was made for present (2018) and future (2030) scenarios varying the energy vector pathways and technologies. The TTW analysis was carried out using two different standard driving cycles, four ranges

(100 km, 200 km, 300 km and 400 km) and dynamic models of vehicles. In order to compare the powertrains, five relevant indexes were proposed, Total Energy Efficiency, Reciprocal of Linear Energy Density, Charging time Emission Index and Vehicle Gravimetric Energy Density. Qualitative analysis was done comparing the results of the indexes proposed for each step, driving cycle and range. Finally a quantitative analysis was performed using a multiphysics index (Integrated Sustainability Index). The results show that the use of dynamic models in the analysis allows to evidence how the powertrains behaviors change with the driving style.

From the ISI analysis it could be concluded that:

- The HEV is the best choice for the present scenario and for short and medium terms.
- In the long term, FCHEV for all ranges and BEV for shorter ranges seem to be competitive choices if the renewable energy production share of the energy matrix increases reasonably.
- For the cleaner powertrains to be competitive within the WTW scope, the hydrogen production should be powered by clean and renewable energies and the renewable energy share in the electric matrix needs to be at least 47% as shown in the scenario proposed for the year 2030.

It should be noted that for the construction of the scenario 2030 the TTW technologies were the same as the scenario 2018, and therefore no advances were considered in terms of the charging time and gravimetric density of the batteries.

Acknowledgments

This work was partially supported by the project PICT 2015 Nº0145, the project PIO Nº15920150100001CO and project SECyT-UNC 2014 (Nº30720130100644CB). The authors acknowledge the contribution of CONICET-UNCA, MINCyT, SECyT-UNC and the FCEFyN-UNC Aeronautical Department.

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