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Exploring the Introduction of Plug-In Hybrid Flex-Fuel Vehicles in Ecuador

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Abstract: In Europe, diesel combustion is being banned due to the NO_x and $PM_{2.5}$ emissions impact on air quality. The bus sector is being electrified and is increasing its use of alternative fuels, such as natural gas (in spark ignition engines) and bioethanol (in compression ignition engines), to reduce such harmful emissions. Even if a diesel bus is equipped with selective catalytic reduction (SCR), its NO_x emissions are reduced its but produces more NH_3 emissions that are $PM_{2.5}$ precursors. In developing countries, the air quality is still barely monitored, however, the air quality issue is well known and is being addressed. Moreover, the Ecuadorian sugar cane industry is seeking ways to increase its ethanol production. This is the ideal framework to explore a new technology and energy source in developing economies such as Ecuador. This paper explores the impact of the Ecuadorian diesel bus fleet conversion to hybrid compression ignition ethanol (HEV-ED95), hybrid diesel and plug-in hybrid flex-fuel using electricity and internal combustion engine ICE-E20 and ICE-E100. The impacts are measured in terms of final energy consumption, criteria pollutant emissions (NH_3, NO_x, $PM_{2.5}$) and 100 years global warming potential in a well-to-wheels framework. For the tank-to-wheels data the method follows the typical values of conversion efficiency from final to useful energy (cross checked with a microsimulation model), the Tier 2 European Environmental Agency approach combined with ethanol influence on compression ratio, lower heating value, criteria emissions taken from a literature review, and well-to-tank emission factors for electricity (10–58% thermal natural gas or coal powerplant contribution), for ethanol from banana industry wastes (ED95, E20 and E100), gasoline and diesel from US databases. A discussion on whether sugarcane biorefineries are necessary is highlighted in the results. All input parameters have an uncertainty range between a minimum and a maximum and the probability for each is giving by a uniform distribution.

Keywords: final energy; new bus technology; NO_x; $PM_{2.5}$; NH_3; ethanol

1. Introduction

The transport sector contribution to crude oil depletion, climate change, and air quality degradation is worrisome. For example, according to the International Energy Agency (IEA) in 2016 the transport sector was accountable for 25% of greenhouse gas (GHG) emissions. According to the same source, it also consumes 98% of crude oil-based fuels. Additionally, road transport represents 40% of NO_x emissions, and is the main source of $PM_{2.5}$ in cities.

It is very likely that the focus on reducing NO_x emissions cause an increase in NH_3 slip aggravated by catalyst ageing [1,2]. Ammonia is an inorganic compound that, in presence of acid gases, can generate atmospheric ammonium aerosol salts [3]. Knowledge of NH_3 tailpipe emissions is therefore important.

The road transportation sector in Ecuador is characterized by its use of fossil fuels as the main source of energy. According to INEC (the Spanish acronym for Instituto Nacional de Estadísticas y Censos—National Institute of Statistics and Census in English), the transportation sector emitted 18.5 million tons of GHG, which correspond to 42% of the emissions from all sectors [4]. Due to the accelerated urbanization in the main Ecuadorian cities, local governments have been forced to implement new transport systems such as bus rapid transit (BRT). The most economical way to commute in Ecuador is by bus, which is also the most used means of transport. Counting regional, urban, public and international buses, there are approximately 23,400 buses where 98% (23,056) correspond to diesel-based buses and the other 2% (380) are gasoline-based buses, mainly used by schools. Recently, a bus line in Guayaquil purchased 20 electric buses for its daily operations, becoming the second South American city to have an electric bus fleet.

In 2010, the Eco País E5 Pilot Program (E5 = 5% ethanol content in gasoline type rated above 85 octanes) started in the cities of Guayaquil and Durán. Initially, the government aimed to increase the ethanol blend with gasoline from 5 to 15% by 2016. However, in order to reach this target, 400 million litres (L) of ethanol are needed per year. The sugarcane cultivated area must add 66 thousand hectares to the existing 79 thousand hectares. By 2015, this program covered 86 percent of demand for extra fuel in the Guayas Province. Ecuadorian sugarcane and alcohol producers were able to produce 80 million L of ethanol. Ecuador's three major sugarcane companies produce most of this ethanol: Valdez with Codana, San Carlos with Soderal and Coazucar with Producargo.

Banana industry wastes were explored as another potential source of ethanol [5,6]. These studies claim that Ecuador has the potential to produce an additional 118–266 L ethanol/ha on a yearly basis from this feedstock. Considering the roughly 150,000 ha in banana production, this would mean an extra 40 million L of ethanol a year.

Ecuador is also experiencing a change in electric power generation, moving heavily to renewables [7]. By 2014, Ecuador had an installed capacity of 5299 MW, with a thermal-based capacity share of 21%, an internal combustion engine share of 25%, a hydro-based capacity of 42%, and the remainder from biomass, solar and wind-based capacity. The government forecasted that this capacity would be approximately 7800 MW by 2018, with the main contribution coming from large-scale hydro. In 2017 the mix was 56.1% renewables and 43.9% non-renewables with distribution losses of 12.1%.

By May 2017, Ecuador presented its National Plan of Energy Efficiency (PLANEE, for its acronym in Spanish) whose objective was to use electricity in an efficient way and to include the promotion of new technologies in the transportation sector [8,9]. To the best of our knowledge, there is no information regarding possible pollutants mitigation achievements in the mass transportation sector in Ecuador.

This paper aims at exploring different bus concept options and their impacts on final energy consumption, air quality and 100 years global warming impact. The bus concepts are: compression ignition running on diesel ($ICEV_{CI}$), hybrid with compression ignition engine running on diesel HEV_{diesel}, hybrid with compression ignition engine running on ethanol-based fuel for diesel engines (ED95) HEV_{ED95}, and plug-in hybrid with flex-fuel spark ignition engine, running on ethanol E20 and E100 $PHEV_{flex}$.

The impacts are measured in terms of final energy consumption, NO_x, $PM_{2.5}$ and NH_3 (converted to PM2.5 equivalent), and CO_2eq through different replacement scenarios. NH_3 is already included in standards by imposing a limit of 10 ppm, for SCR equipped buses and based on Equation (3) from Stelwagen and Ligterink [2], this would probably mean 46 mg/km NH_3 slip. Ecuador follows European emission standards so we are going to stick with European emission models for the tank-to wheels (TTW) data.

2. Materials and Methods

The aim of this study is to compare the final energy consumption and local environmental impacts of six scenarios considering different fuels (diesel, ethanol blend and electricity) and bus technologies (compression ignition, spark ignition and plug-in hybrid flex-fuel) (Table 1). The scope of the study is the so called well-to-wheels (WTW) analysis. It is divided into tank-to-wheels (TTW) according to the matrix of powertrains/fuels in Table 1 and well-to-tank (WTT) according to Table 2.

Table 1. Matrix for TTW energy consumption and emissions calculations.

Technology/Fuel	Diesel	E20	E100	Electricity
ICEV compression ignition (CI)	x			
HEV (CI)	x		x	
PHEV spark ignition (SI)		x	x	x

The general formulation for final energy consumption (TTW) of a fleet with several powertrain technologies and vehicle ages (equivalent to standard) is:

$$EC = \sum_{y} \sum_{m\ (liquid/gas\ fuel)} \left(NV_{m,y,z} \times M_{m,y,z} \times FI_{y,z,m} LHV_m \rho_m\right) + \sum_{y} \left(NV_{electric,y,z} \times M_{y,electric} \times FI_{y,z,electric} * 3.6\right) \quad (1)$$

where EC stands for the final energy consumption of the fleet (MJ/year); $M_{m,y,z}$ (km/year), is the average annual distance driven per vehicle of category y, standard z, and fuel m, excluding electric miles; $N_{m,y,z}$ is the number of vehicles of category y, standard z, and fuel m; $FI_{y,z,m}$ is the average fuel intensity of the vehicle (L/km or kWh/km); and LHV_m is the lower heating value of the liquid/gas fuel m.

The general model for emission, E_x, where x stands for each pollutant, NO_x, $PM_{2.5}$ or NH_3 is:

$$E_x = \sum_{m(liquid/gas\ fuels)} \sum_{y} \sum_{z} \left(NV_{m,y,z} \times M_{m,y,z} \times EF_{x,m,y,z}\right) \quad (2)$$

where, $EF_{x,y,z}$ (g/km), is the specific emission factor of pollutant x, for vehicle category y, emission standard z and liquid fuel m; E_x is the emissions of pollutant x.

Ammonia is a colourless gas present in the atmosphere, which reacts with acid gases (H_2SO_4, HNO_3, etc.) to produce atmospheric ammonium aerosol salts and particles such as ammonium sulfate ($[NH4]_2SO_4$), ammonium bisulphate (NH_4HSO_4), ammonium nitrate (NH_4NO_3), and ammonium chloride (NH_4Cl). Knowledge of NH_3 tailpipe emissions is therefore important. To convert NH_3 tailpipe emissions into PM2.5 equivalent the following chemical reactions will be considered:

$$2NH_3(gas) + H_2SO_4 \Leftrightarrow (NH_4)_2SO_4\ (particle)$$

$$NH_3(gas) + HNO_3\ (gas) \Leftrightarrow NH_4NO_3\ (particle) \quad (3)$$

$$NH_3(gas) + HCl\ (gas) \Leftrightarrow NH_4Cl\ (particle)$$

The mass to mass ratio of particle to NH_3 for these equations is, respectively, 132.14/34.062, 80.043/17.031 and 53.491/17.031. An average factor of 3.91 is assumed for the $PM_{2.5}$ equivalent. Fuel consumption and emissions for new technologies will be compared with the baseline scenario to analyse their future insertion.

Our approach is based on real data from conventional bus fuel intensity to which we then applied final to useful energy efficiencies to get our exploratory flex-fuel engine PHEV final ethanol and electricity consumption. This is a simplified approach and was “cross checked” against the ADVISOR microsimulation model [10–12] for ICEV, HEV and PHEV over a specific driving cycle (driving schedule). Figure 1 presents the procedure schematic.

Table 2. Matrix for WTT CO2eq emission factors.

Energy Source	Min	Max
Diesel [13] (gCO_2eq/MJ)	17.5 (621.1 *)	23.5 (834.0 *)
Gasoline [13] (gCO_2eq/MJ)	19.7 (654.4 *)	26.3 (873.4 *)
electricity (10% thermal based) g/kWh	34.1 (natural gas)	102.4 (coal)
electricity (58% thermal based) g/kWh	198.0 (natural gas)	593.9 (coal)
ethanol from banana waste [6] (g/MJ)	23.6 (540.2 *)	23.6 (540.2 *)

* g/L; using 794 kg/m^3 and LHV 28.8 MJ/kg for ethanol; 0.845 kg/L, with LHV of 42 MJ/kg for diesel; 0.755 kg/L and LHV of 44 MJ/kg for gasoline.

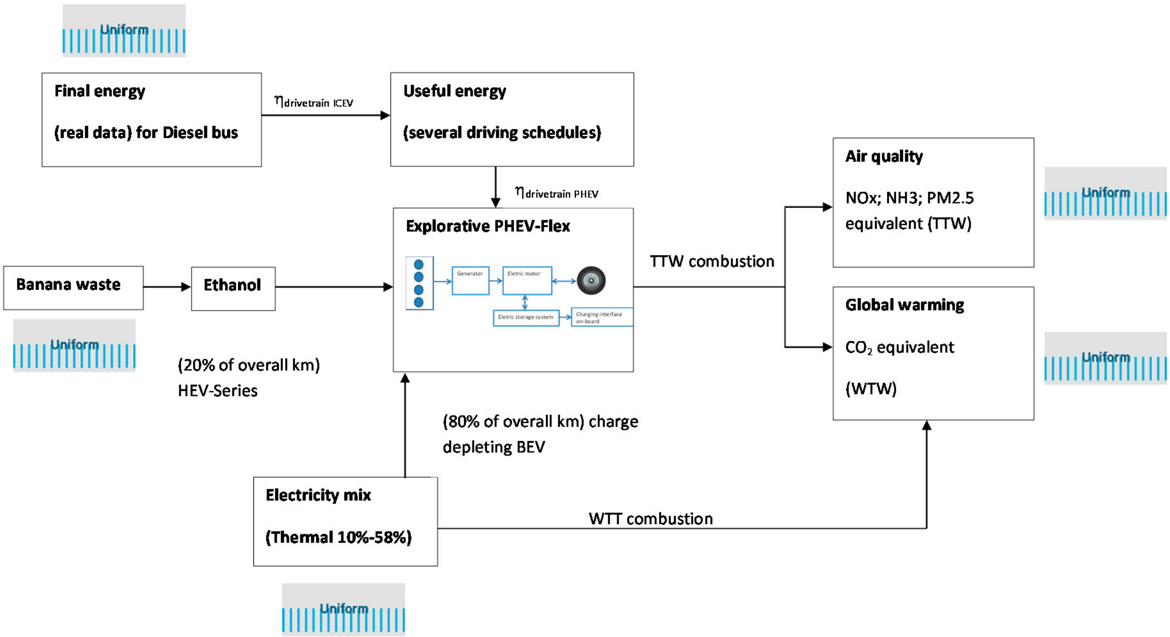

Figure 1. Simplified model scheme for air quality indicators tank-to-wheels (TTW) and global warming impact well-to-wheels (WTW) evaluation/graphical abstract.

As a "cross check" of the final to useful energy conversion efficiencies, the driving cycle was the World Harmonized Heavy Duty cycle [14], with 40 km/h average speed, 20 km distance and 12 stop-&-go situations.

2.1. Reference Scenario-100% ICEV Diesel Fleet

The inventory of the number of bus vehicles in Ecuador and the fuel used was obtained from the Transport Statistics Yearbook published by the Instituto Nacional de Estadísticas y Censos (INEC) [4]. The fuel consumption, Equation (1) and emissions, Equation (2), were estimated using a bottom-up approach and following the guidelines of the Tier 2 methodology of the European Environmental Agency (EEA) (previous CORINAIR) [15].

The average annual distance was calculated using a 2016 database provided by the Ecuador Municipal Transit Authority of Guayaquil. The database presents odometer readings from several buses during inspection. Most of the buses have more than one inspection during the year, thus, two mileage records. Hence, the subtraction of two mileages recorded at different times divided by the time between both records gives us the average daily distance travelled. The other inputs needed for fuel consumption and emission calculations such as fuel intensity and emissions factors are shown in Table 7. The overall efficiency is a product of the powertrain components efficiency.

The efficiency of the diesel bus engine (ICEV buses, Figure 2) was assumed to be 38–47% [16,17], including heat losses, friction, pumping work and auxiliaries like lights, power steering, brake booster and a sound system, etc. The transmission efficiency is typically 70–80% [18]. Therefore, we assume

26.6–37.6% for the diesel driveline (TTW efficiency) diesel density is 0.845 kg/L, with an LHV of 42 MJ/kg [19]. These values are to be "cross checked" using microsimulation software. Diesel engine technology will be referred to as compression ignition (CI) and spark ignition (SI) engine technology.

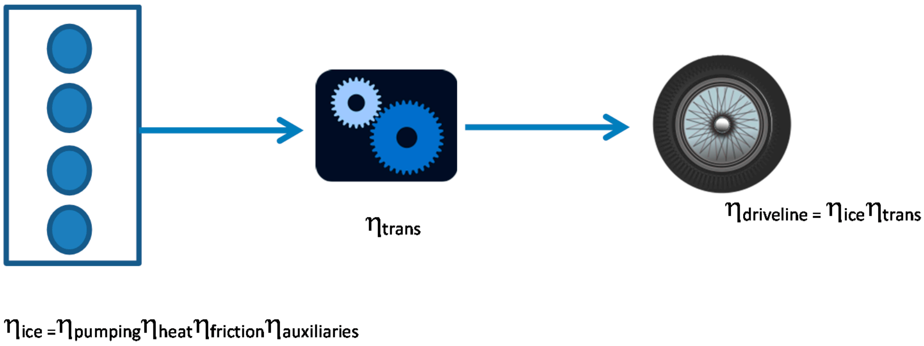

Figure 2. Conventional compression ignition/spark ignition powertrain.

2.2. Hypothetical Scenarios HEV with ED95

It is already possible to run a CI engine with ethanol by using a higher compression ratio and additives. This HEV-ED95 runs on 95% ethanol and 5% additives to help self-ignition. A bus with this technology is commercialized by Scania. The OmniLink ethanol hybrid bus is based on series hybrid technology (S-HEV) (Figure 3 and Table 3).

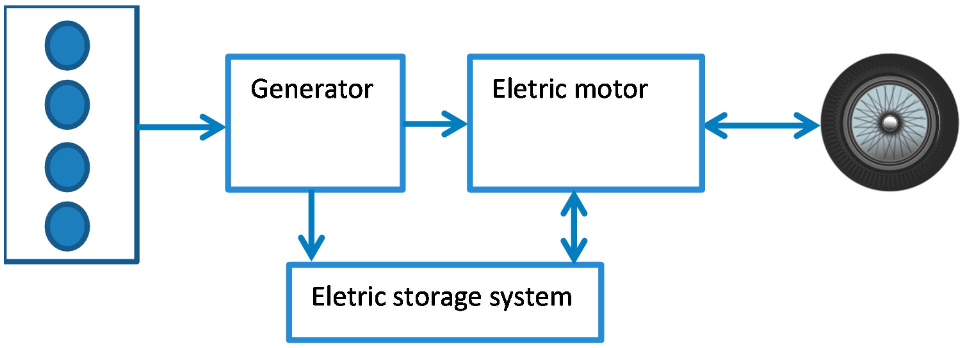

Figure 3. HEV-ED95 hybrid powertrain.

Table 3. Technical specifications of Scania Omnilink HEV-ED95 bus.

Electric Motor	Voith TFM Max 150 kW/Max 2750 Nm
Energy Storage System	Maxwell supercapacitor 0.4 kWh
Passenger Capacity	114
Curb weight	16 ton
Engine	Max. output 270 hp (198 kW) Max. torque between 1250 Nm No. of cylinders 6 Displacement 9 dm^3 Compression ratio of 28:1

For real measurements, we only found a VTT Technical Research Centre of Finland Ltd. study where an HEV-ED95 bus was measured using a chassis dynamometer roller bench., recording 16.5 MJ/km for empty bus fuel consumption, 5.58 g/km for NO_x, and 0.037 g/km for PM [20]. This data is available through the LIPASTO traffic emissions database. In terms of TTW efficiency, and according to this report, the real measured fuel consumption was 0.73 L/km.

2.3. Hypothetical Scenarios PHEV with E20 and E100

The flex-fuel SI engine in a hybrid powertrain is already being addressed by passenger car manufacturers, e.g., Toyota presented an initial design of the first hybrid flexible-fuel vehicle (Hybrid FFV), in Sao Paulo, Brazil. The efficiency gains could be up to 6% with ethanol blends [21]. However, this technology is not yet available on buses. This is the reason our study is exploratory and we do not have experimental data on this new hypothetical bus type. Additionally, since there are several energy management strategies for the PHEV powertrain, the flex emission data must be estimated based on emission factors. Our reasoning is therefore supported by efficiency logic and available literature data.

Usually, the efficiency of a diesel engine is 30% higher than η_{ice} of SI engines [22]. Hence the TTW efficiency for the hypothetical flex-fuel driveline is (26.6/1.3 * 1.06_37.6/1.3 * 1.06; or 21.7_30.7%). The driveline efficiency ratio between SI and CI is near the 85% found in literature [23].

The lower heating value of the blend is calculated by Equation (4), where "blend" stands for ethanol %, e.g., E20 would be 20%:

$$LHV_{blend} = (1 - blend/100) * LHV_{gasoline} + blend/100 * LHV_{ethanol} \quad (4)$$

The density follows the same procedure. Ethanol density is 794 kg/m^3 and LHV 28.8 MJ/kg [19]. Gasoline 755 kg/m^3 and 44 MJ/kg [19]. The effect ethanol blends have on CO_2 emissions is direct from combustion mass balance (assuming C_8H_{18} for gasoline), the equation is:

$$ECO_2\ [kg/kg_{fuel}] = (1 - blend/100) \times 3.0877 + blend/100 \times 1.9130 = 0.0117 * blend + 3.0877 \quad (5)$$

For the effect of ethanol blend on NO_x, NH_3 and $PM_{2.5}$ criteria pollutant emissions were reviewed in the literature. Due to the lack of data for buses, the effect was taken from experimental studies on light-duty vehicles by Suarez-Bertoa et al. [24] which indicate absolute emission factors for E5, E10, E15, E75, and E85. Hubbard, Anderson and Wallington [25] indicated relative differences between E0 and E10, E20, E30, E40, E55, and E80. Additionally Table 4 [26] includes several studies for finding E10 and E20 impacts on NO_x and $PM_{2.5}$ and shows an average impact of −11.8% and −17.1% for NO_x; and −6% and −36% for PM, respectively. From Table 4, we assume E80 impacts to be the same as for E100, or −49% for NO_x and 153% for NH_3. In our study we assume the correction factors, stated in Table 5. The tendency for NH_3 to increase with ethanol blends and NO_x and PM2.5 decrease is noteworthy.

Table 4. Emission factors found in the literature for flex-fuel vehicles [24,25].

	[24]			[25]		
	NO_x (mg/km) WLTP Cycle	**NH_3 (mg/km) WLTP Cycle**	**$PM_{2.5}$ (mg/km) WLTP Cycle**	**NO_x (g/mile) FTP Cycle**	**NH_3 (g/mile) FTP Cycle**	**$PM_{2.5}$ (g/mile) FTP Cycle**
E0	NA	NA	NA	0.0544	0.0353	NA
E5	62	6	NA	NA	NA	NA
E10	42	16	NA	0.0472	0.0408	NA
E15	51	14	NA	NA	NA	NA
E20	NA	NA	NA	0.0316	0.0638	NA
E30	NA	NA	NA	0.0245	0.0642	NA
E40	NA	NA	NA	0.0209	0.0705	NA
E55	NA	NA	NA	0.0293	0.0968	NA
E80	NA	NA	NA	0.0261	0.0896	NA
E85	19	26	NA	NA	NA	NA

Table 5. NO_x, NH_3 and $PM_{2.5}$ assumed correction factors.

	NO_x	NH_3	$PM_{2.5}$
E10	−12%	+10%	−6%
E20	−17	+52%	−36%
E80	−49	+153%	−36%
E100	−49	+153%	−36%

Criteria pollutants were obtained using Table 4 correction factors applied to Tier 2 emission factors for SI technology buses.

The new plug-in hybrid bus technology was based on the plug-in 7900 Electric Hybrid bus from Volvo (Table 6 and Figure 4). The internal combustion engine was replaced by a SI engine with the same rated power. Efficiency reasoning is used. In the literature [27–30]. The TTW efficiency varies but typically we may find 70–85% for a pure electric vehicle, BEV, depending on the driving cycle.

Table 6. Technical specifications of plug-in 7900 Electric Hybrid bus from Volvo (PHEV).

Electric Motor	Max 160 kW/Max 1200 Nm
Energy Storage System	Lithium ion battery 76 kWh
Transmission	Volvo 2-speed automatic transmission
Charging System	Opportunity charging—conductive charging system—roof mounted. Fully automatic, fast charging. Fast charging time: up to six minutes.
Passenger Capacity	83
Curb weight	12 ton
Engine Volvo D5K240 EU6	Max. output 240 hp (177 kW) Max. power at 2200 rpm Max. torque between 1200–1600 rpm 918 Nm No. of cylinders 4 Bore 110 mm Stroke 135 mm Displacement of 5.1 dm^3 Compression ratio of 17.5:1 Oil-change volume, including oil filters approx. 18.7 L

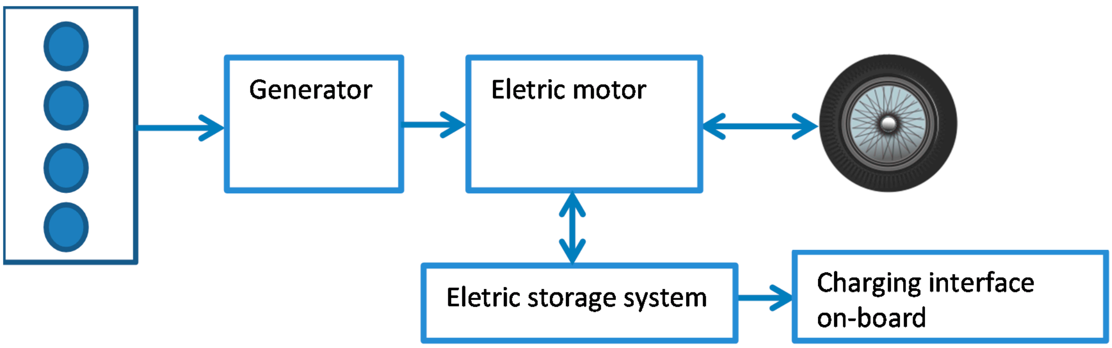

Figure 4. PHEV flex fuel powertrain.

According to the all-electric efficiency range assumed, 80% of the mileage is electric and 20% flex-fuel, were assumed to have an efficiency of 70–85% for all-electric and 21.7–30.7% for flex-fuel. That is, we assume a charge depleting energy management strategy and the 80% of km are like a pure electric vehicle, depleting the battery while the internal combustion engine is switched-off. The remaining km are like a hybrid internal combustion engine vehicle. The range is necessary because in our approach we want to cover most possible real driving situations and not just a specific driving cycle. The overall inputs to Equations (1) and (2) are given in Table 7.

The uncertainty sources were identified: fuel consumption/drivetrain efficiencies; and criteria emission factors. A maximum and minimum range in inputs were reflected in the model outcomes. CO_2 emissions as a function of the fuel consumption had the same uncertainty levels. Regarding NH_3, the minimum $PM_{2.5}$ equivalency factor was 3.16 and the maximum 4.70. This gave us a $PM_{2.5}$ equivalent range. For NO_x and $PM_{2.5}$, the literature report usual uncertainties of 16% on average [31], without fuel correction and using the Tier 3 approach from EEA. A Tier 2 approach such as ours should have higher levels of uncertainty. Nevertheless, we stick to 16%, to at least have a range of emissions. Uncertainty in the model input parameters is considered and is reflected in the results, by a uniform distribution (a minimum and maximum range).

Table 7. Inputs for fuel consumption and emissions calculations.

Technology *y*	Standard *z*	Fuel *m*	M Annual mileage (km/y)	N Number of Buses	FI L/km or kWh/km 1)	EF_{NOx} 2) (g/km)	$EF_{PM2.5}$ (g/km)	EF_{NH3} (g/km)
conventional ICEV (compression ignition)	Euro III	Diesel	78,767	23,056	$FI_{diesel} = 0.4–0.56$ [32] 0.36 tier 2 0.46 VTT Capturing variations with the driving cycle	9.38	0.207	0.0029
conventional ICEV (compression ignition)	Euro V	Diesel	78,767	23,056	FI_{diesel}	3.09	0.0462	0.011
HEV (compression ignition)	-	Diesel	78,767	23,056	0.3–0.42 (less 25% than FI_{Diesel} [33])	0.98 [34]	0.0231 less 50% than conventional ICEV [35]	0.0046 [34]
HEV compression ignition	Euro V	E95	78,767	23,056	0.73 [20]	5.58 [20]	0.037 [20]	NA 3)
ICEV (spark ignition) reference for applying Table 3	-	-	-	-	-	2.5 (spark ignition urban bus [15])	0.005 (spark ignition urban bus [15])	0.0019 (spark ignition heavy-duty vehicle [15])
PHEV	-	electricity	80% of 78,767	23,056	$\frac{FI_{diesel} * \rho_{diesel} * LHV_{diesel} * \eta_{driveline\ Diesel}}{3.6 * \eta_{driveline} Eletric}$	0	0	0
PHEV	-	E20	20% of 78,767	23,056	$FI_{diesel} * \frac{\rho_{diesel} * LHV_{diesel} * \eta_{driveline\ Diesel}}{\rho E20 * LHVE20 * \eta_{driveline\ E20}}$	2.0 applying Table 3	0.003 applying Table 3	0.0029 applying Table 3
PHEV	-	E100	20% of 78,767	23,056	$FI_{diesel} * \frac{\rho_{diesel} * LHV_{diesel} * \eta_{driveline\ Diesel}}{\rho E100 * LHVE100 * \eta_{driveline\ E100}}$	1.3 applying Table 3	0.003 applying Table 3	0.0048 applying Table 3

1) When electricity; 2) NO_2 equivalent; 3) 10 ppm limit in Euro VI, equivalent to a minimum of 0.05 g/km assuming the stoichiometric combustion ratio of 9, a lambda of 18, typical for idle, and exhaust molar mass of 29 kg/kmol.

3. Results

Runs of the ADVISOR microsimulation model [10–12], for one specific driving cycle with 12 stops, were crosschecked with reviewed literature data on powertrain component efficiency (Figure 5). The fuel converter (ICE) efficiency of a conventional diesel bus, an HEV and a PHEV (with charge depleting management strategy) buses are depicted, as well as their powertrain component efficiencies.

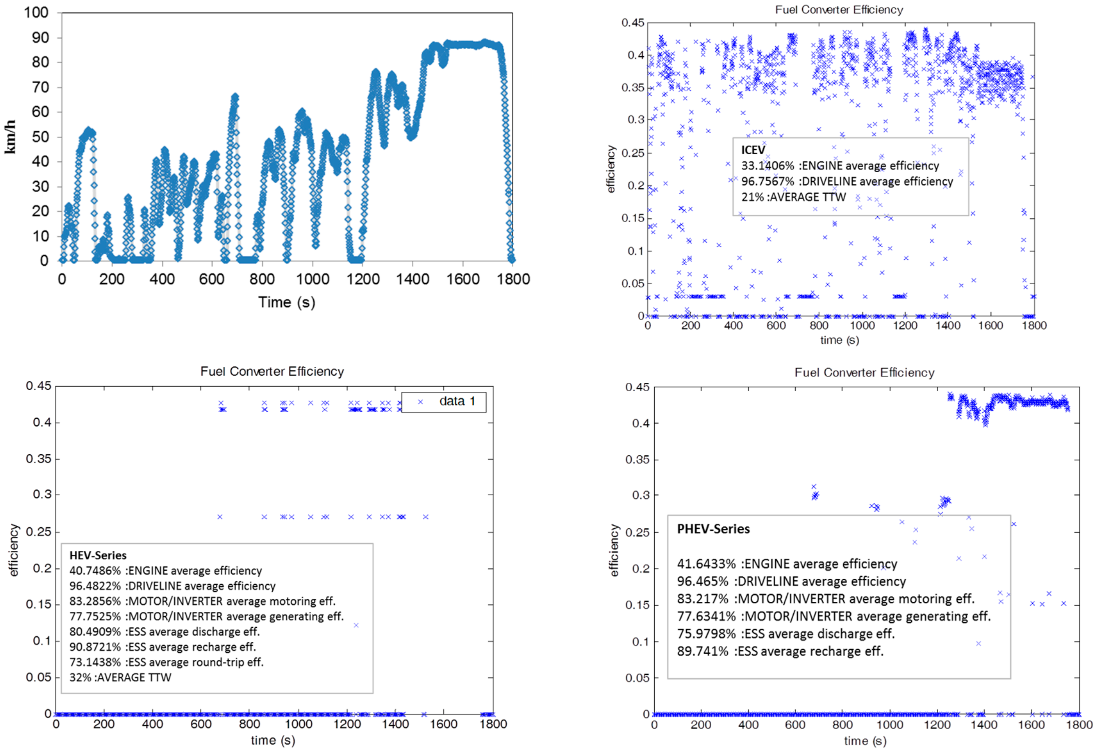

Figure 5. ADVISOR model efficiencies for a specific driving cycle and PHEV energy management (average speed 40 km/h, distance 20 km, 12 stop-&-go situations). "Cross check" of efficiency assumptions.

As we can see in Figure 5, the efficiencies fall in the ranges reviewed so we stick with our simplified approach for the analysis of WTW. Considering the macro approach of fuel intensity and powertrain efficiency ratio seems to be suitable and intends to cover as much of driving situations as possible. Considering this macro approach, the final energy consumption is depicted in Table 8 for the reference and alternative scenarios.

Table 8. Final energy consumption by source and per year, with uncertainty.

	Electricity GWh	Diesel ML	Gasoline ML	Ethanol ML
ICEVdiesel-Reference Euro III bus fleet	-	835.38 (654–1017)	-	-
HEVdiesel	-	626.54 (490–763)	-	-
HEVED95	-	-	-	1325.72
PHEVflexE20	2215.99 (1642–4385)	-	164.73 (105–326)	41.18 (26–82)
PHEVflexE100	2215.99 (1624–4385)	-	-	281.34 (179–557)

So, if Ecuador decides to hybridize the bus fleet on ED95, it will have to produce roughly 1326 million litres of ethanol a year to satisfy the final energy demand. This means that the potential ethanol production either from sugarcane (80 million L a year) or banana industry waste (40 million L a year) will not be enough. If the option is to move forward with a $PHEV_{flex}$ fleet, the ethanol demand is much lower, 41–281 million L, which could not yet be met by banana industry waste. Ethanol production through the sugarcane industry could meet around 42% of the maximum ethanol production required for this case. The sugarcane industry must, in any case, provide most of the required fuel.

In terms of air quality, of course, the PHEV scenarios would be better because it was assumed that 80% of the mileage is all-electric, with zero local emissions. Nevertheless, the introduction of ethanol could increase NH_3 particle precursors and if we look to the equivalent $PM_{2.5}$ in Table 9, the hybrid

ED95 fleet could be the worst-case scenario. The higher NH_3 emissions in HEV_{diesel} are due to the SCR NOx exhaust aftertreatment system and the reduced $PM_{2.5}$ to the particle filters.

Table 9. Criteria pollutants for the Ecuadorian bus fleet in ton/year, with uncertainty.

	NO_2	$PM_{2.5}$	NH_3	$PM_{2.5}$ Equivalent
ICEV-Reference Euro III bus fleet	17,034.6 (14,309–19,760)	375.9 (318–434)	5.3	396.5 (338–455)
HEV diesel	1779.7 (1495–2065)	42.0 (35–49)	83.5	368.3 (364–376)
HEV ED95	10,133.6 (8512–11,755)	67.2 (78–95)	95.3	439.7 (429–450)
PHEV E20	753.7 (633–874)	1.2 (1–1.3)	1.0	5.3 (5.1–5.4)
PHEV E100	463.1 (389–537)	1.2 (1–1.3)	1.7	8.0 (7.8–8.2)

The TTW CO_2 emissions are a part of a future study on a WTW approach and are depicted in Figure 6. It is worth noting that there is considerable mitigation of TTW CO_2 emissions, around 78–80% when conventional fleet buses are replaced with plug-in hybrid buses It is interesting to note that the HEV_{ED95} has higher TTW CO_2 emissions due to the higher fuel consumption phenomena that overlap the lower CO_2 formation per litre of ethanol burned in comparison to diesel fuel (1.5 $kgCO_2$/L ethanol versus 2.7 $kgCO_2$/L diesel). The diesel-ethanol HEV-ED95 technology energy consumption and CO_2 emissions were derived from the LIPASTO database on-road measurements and have no reported uncertainty.

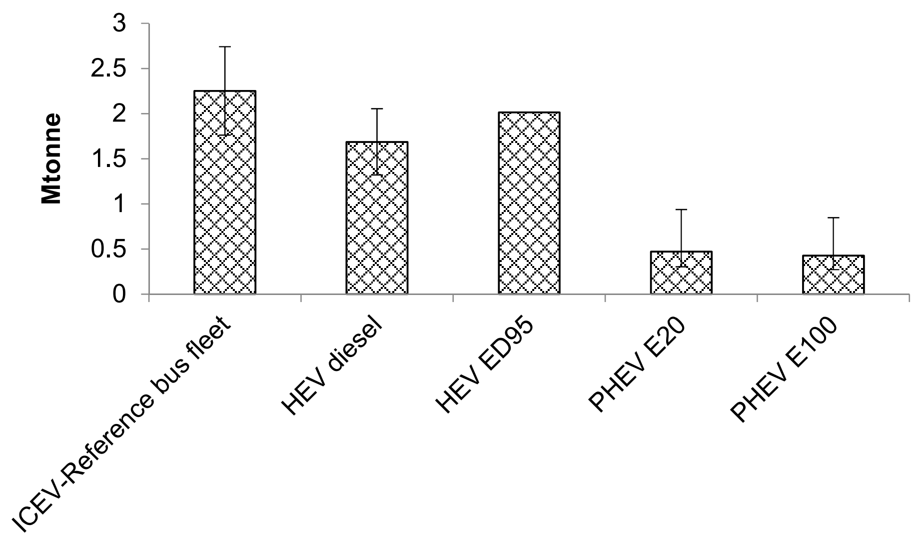

Figure 6. TTW CO_2 emissions for the Ecuadorian bus fleet in millions ton/year, with uncertainty (range based with uniform distribution).

Additionally, observing the WTW values in Figure 7, clearly electrification of the bus fleet has more positive impacts on the air quality and global warming impact than moving to a bioeconomy bus fleet system. However, the flexibility of supplying a PHEV with three possible energy sources instead of just electricity is noteworthy.

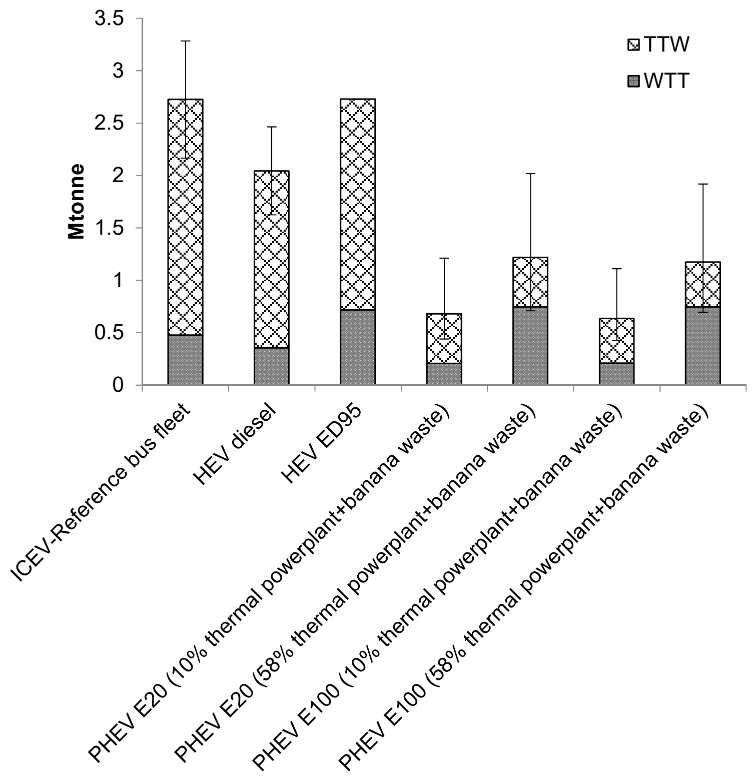

Figure 7. WTW CO_2 emissions for Ecuadorian bus fleet in millions ton/year, with uncertainty (range based with uniform distribution).

4. Discussion

These are preliminary results due to the limitations/constraints of the work. One main limitation is the lack of hybrid CI diesel and hybrid ED95 bus data in the EEA emission inventory guidebook [15]; therefore the bus technologies are not compared using the same database. The ethanol effect on $PM_{2.5}$ in flex-fuel engines is also barely reported in the literature and should be explored experimentally. NH_3 emissions need more experimental data because are they are particle precursors and are already limited in new European and American regulations to 10 ppm in exhaust gases. These values are barely seen in the reviewed literature. However, the uncertainty given in the results could partially reflect these weaknesses and be taken as a preliminary result indicating whether Ecuador should pursue a bioeconomy.

In this context, the food vs. biofuels discussion will be intensified. However, Ecuador may choose to continue producing sugar and its derivatives and producing ethanol through surplus bagasse, in a biorefinery context. For example, Cavalett et al. [36] and and Corrêa do Lago et al. [37] definitely demonstrate the positive sugarcane conditions for the development of second generation ethanol (non-food competitive) at least at the Brazilian context. Again the flexibility of a vehicle running on three possible fuels is highlighted. Moving heavily to renewables in the future and having only 10% of electricity provided by thermal powerplants (coal or natural gas) should be addressed.

5. Conclusions

As an explorative study this paper shows some novel concepts in terms of a new possible PHEV bus powertrain and a conversion factor for NH_3 emissions to $PM_{2.5}$ equivalent emissions. The simplified model of using a range of fuel intensities and typical final to useful energy conversion efficiencies was crosschecked with a microsimulation model that allows the efficiency data variation at various speeds and acceleration/deceleration rates.

The metrics calculated in this research were, final energy consumption (by source), air quality related pollutants, NO_x (as NO_2 equivalent), NH_3, and $PM_{2.5}$ equivalent, and 100 years global warming potential (as CO_2eq).

If the diesel energy source is to be kept, hybrid technology is a good option for a replacement, reducing fuel consumption and TTW CO_2 emissions by 25%, but, despite the particle filters, only reducing 7% the $PM_{2.5}$ equivalent emissions.

If an ethanol energy source is seen as the future, and energy supply flexibility to the bus is a priority, the best option to reduce emissions will be the plug-in hybrid flex-fuel vehicles. However, Ecuador still needs more investment in ethanol production. The current capacity (considering ethanol production through sugarcane and banana waste) will not be enough to satisfy the demand and it will be imperative to boost ethanol production through larger extensions of cultivated area and sugarcane biorefineries. These new technologies will provide a 55–77% CO_2eq reduction, even if coal is used in the thermal powerplant, on a heavy renewables penetration scenario.

A future study on sugarcane biorefineries sustainability in Ecuador will bring the carbon footprint (well-to-wheels) benefits of such PHEV flex-fuel bus system to the discussion.

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