Biofuels as a Shortcut to Brazilian Light Fleet Decarbonization

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ABSTRACT

The decarbonization of the light vehicle fleet faces the challenges of electrification around the world in terms of vehicle costs, battery technology, recharging infrastructure and fleet replacement. Brazil offers the possibility of decarbonization by intensifying the use of biofuels associated with the current low carbon intensity of the electrical energy matrix, both with similar carbon footprint. This work applies life cycle assessment to compare the decarbonization effectiveness of Brazilian light fleet of vehicles, between electrification and biofuels, adjusting energy consumption for real use conditions. The option for battery electric vehicles considers the extremes of the vehicle categories, subcompact and sport utility, while the hybridization option considers a large car, portraying the reality of the Brazilian market. The analysis proposes adjusting the carbon intensity factors of the vehicle production according to the production location. Use on short urban journeys, a critical condition for internal combustion engines, is based on an innovative mathematical model of the impact of the cold phase on fuel consumption. The results indicate the estimated time for the effective advantage of electrification in mitigating greenhouse gas emissions in urban cycle.

INTRODUCTION

The light fleet electrification is an important route for decarbonization. Compared to a conventional vehicle powered by internal combustion engines (ICEV), considerably intense in greenhouse gas (GHG) emissions when running on non-renewable fuels, the electrified vehicles are more efficient to convert the electricity in movement, besides the capability to recover part of the vehicle kinetic energy during deceleration through the electric motor coupled to a high voltage battery, which represents a competitive option when running on sustainable electricity.

The vehicle usage is determinant to define the effectiveness of some solution in decarbonization. Conventional ICEVs present better efficiency in road cycle due to higher engine loads that is an operating condition in which internal combustion engines are more efficient. Even with the engine running on stabilized and most efficient temperatures in urban cycles, it demands lower engine torque, requiring the engine to operate in partial loads, with reduced efficiency due to pumping losses. Moreover, engine high speeds during acceleration, which are more frequent in urban cycles, contribute to greater friction losses penalizing engine efficiency. The vehicle driving in short routes, primarily urban, imposes the influence of the cold phase phenomena on ICEVs. As pointed out by Roberts, Brooks and Shipway [1], by Ye and Mohamadian [2], by Brunetti [3], by Heywood [4] and by Reif [5], during this critical phase, internal combustion engines operates in lower efficiency and consequently higher fuel consumption attributed to: higher friction due to lubricant viscosity increase in low temperatures; engine components and aggregates warm up with energy from fuel; catalytic converter light off strategy by spark retard and/or early exhaust valves opening. Some engine control strategies work to ensure combustion stability during cold phase like cold start enrichment to promote the first combustion reactions, idle speed increase for better turbulence and engine friction compensation, and mixture enrichment during warm up to compensate for fuel condensation on the cold engine walls (choke operation), to ensure acceptable air/fuel mixture inside the combustion chamber. Guilherme et al. [6] experimentally demonstrated the influence of the cold phase of ICEVs on the urban cycle determined by NBR6601 [7]. The importance of cold condition is reinforced by NBR16567 [8] which weights the average use of the light fleet at 20% on daily journeys with less than 12 km, reaching close to 40% for journeys of up to 24 km, which highlights the relevance of this topic. The influence of the cold phase on ICEVs is not so significant in fuel consumption measurement in a combined cycle (NBR7024) [9], determined by 45% of highway cycle and 55% of urban cycle [7], resulting in about 2% increase in fuel consumption. The urban driving cycle comprises cold start, between 20 and 30 °C, and driving in urban cycle through the warmup, in accordance with NBR6601 [7]. The cold phase impact during the first phase of the urban cycle [7] is quite significant, reaching approximately 20% higher fuel consumption according to Rovai [10]. This demonstrates that the vehicle's usage cycle is decisive for the effects of the cold phase of engine operation, with short trips being more sensitive to cold phase. Vehicles technological improvement, encouraged by Brazilian legislation [11, 12] and pointed out by De Salvo Junior, De Souza and De

Almeida [13], by Mosquim and Mady [14], should reduce the impact of cold phase in the future with the use of such a lower viscosity lubricants and aluminum engines, but should increase the impact due to more restrictive pollutant emissions, regulated by PROCONVE in Brazil [15], demanding more aggressive catalytic converter light off strategies.

HEVs and BEVs present opposite behavior to the ICEVs in terms of energy consumption depending on the driving cycle. While ICEVs are more efficient in the highway than in the urban cycle, HEVs and BEVs are more efficient in urban cycle than in highway use. This difference confirms the higher advantages of electrification in vehicle efficiency are revealed in urban cycle, in which electric motors are much more efficient than internal combustion engines in partial load. Highway driving demands higher power and rotation from drivetrain, conditions in which electric motors lose efficiency by friction and heat transfer (cooling). While combustion engines could only cut fuel consumption during decelerations (cut-off), electric powertrains allow the regeneration of part of the vehicle's kinetic energy during these maneuvers. The regeneration capability of electrified vehicles varies mostly with the drive cycle and according to the power capacity of the electric system. The energy recovering is more effective in urban cycles which involve more frequent decelerations, but not so significant in highway conditions, contributing to the greater efficiency of HEVs and BEVs on urban journeys, also observed by Skuza, Jurecki and Szumska [16] and by Mamarikas et al. [17]. Instead dissipating the vehicle kinetic energy through brake system during decelerations, as in conventional vehicles, the electrified vehicles are more effective to recover part of this energy by converting it in electricity by the motor and storing it in a high voltage battery. Higher battery capacity and voltage of the electrical system assures more energy saved for the next vehicle accelerations.

METHODOLOGY

The analysis of the GHG emissions impact by a light vehicle electrification in Brazil was performed considering three options, covering three different vehicle categories of electrified vehicles available in Brazilian market. The comparisons are performed between conventional engine (ICEV, internal combustion engine vehicle) or electrified (HEV, hybrid electric vehicle or BEV, battery electric vehicle) versions with significant differences only in powertrain, avoiding any usage limitation, e.g. in terms of number of occupants and trunk capacity. A large vehicle is compared in its ICEV (L_{ICEV}) and HEV (L_{HEV}) versions. An eventual replacement of an ICEV by a BEV is considered for a subcompact (SC_{ICEV} x SC_{BEV}) and a sport utility vehicle (SUV_{ICEV} x SUV_{BEV}). The vehicle GHG emissions are estimated by a vehicle life cycle assessment (LCA), subdivided in three phases of vehicle: production, driving and recycling.

VEHICLE PRODUCTION – The GHG emissions during the production phase can be estimated by the overall impact of two main subsystems: vehicle body and high voltage battery.

The production impact of the vehicle body should consider the raw material and the manufacturing of each component, besides the impact to construct the vehicle body in an assembling line. This discrete method demands a deep knowledge about each detail of the vehicle which is very difficult to be considered except by the project owner. A simplified method to estimate the vehicle production impact that considers a constant factor to be multiplied by vehicle mass, without the high voltage battery, was proposed by Ellingsen, Singh, and Stromman [18], Buberger et al. [19] and Bieker [20]. The average of the constant factor proposed by Ellingsen, Singh, and Stromman [18] is 4,8 $kgCO_2e/kg$ of vehicle body for a ICEV produced in Europe (EU). According to Transport & Environment [21], this factor is reduced in 10,7% for a BEV given its lower constructive complexity compared to an ICEV, methodology even considered by Bieker [20], and Kelly et al. [22]. The comparison between the discrete and the constant factor methods of GHG emissions for vehicle production was performed by Rovai, Seixas and Mady [23], following Pipitone, Caltabellotta and Occhipinti [24], with the constant factor method resulting in higher production impacts, magnified for conventional vehicles. Vehicle production is very intensive in electricity, since the manufacture of each component and the body stamping, welding, painting and assembling processes, as observed by Weiss et al. [25], by Sullivan, Burnhan and Wang [26], by Egeskog et al. [27], by Evrard et al. [28], by Kelly et al. [22], and by Sacchi et al.[29]. The adjustment of the production impact factor according to the electricity carbon intensity where the vehicle is produced is considered by Bieker [20], by Hill et al. [30], and by Hao et al. [31], based, for example, on steel and aluminum parts. This paper adopts the vehicle production intensity factors linearly corrected with electricity carbon intensity from EPE [32] and proposed by Rovai, Seixas and Mady [23]. The comparative analysis of electricity carbon impact carried out by the same institution, EPE [32], with the same methodology for the considered regions contributes to accurate and reliable results. It should be noted that the analysis carried out with data from 2018, despite the lag time from 2023, is based on the most recent values published by EPE during the development of this study, data also used by Gauto et al. [33]. Furthermore, these values from 2018 are still exempt from COVID19 pandemic effects, which significantly affected each of the regions analyzed in different periods. The EPE [32] values can be compared to other references as a double check, clarifying any doubts regarding distortions: Wu and Zhang [34], Carbon Footprint [35], IEA [36], and EEA [37].

Just like vehicle body, the production of the high voltage battery applied in HEVs and BEVs is also an intense activity in electricity, pointed by Bubberger et al. [19]. The estimative of carbon emissions from high voltage battery manufacturing can be calculated by multiplying the battery's charge capacity by a production carbon intensity factor that includes the mining stage of the materials used which varies with extraction site and battery technology, the manufacturing of the component that is sensitive to the carbon intensity of the electricity consumed in this process. According to Andersson and Böjersson [38], recent studies consider the range from 61 kgCO$_2$e/KWh to 106 kgCO$_2$e/kWh for the carbon intensity factor of high voltage battery production, with the lowest value for production in regions that use energy clean electricity and the highest value for production in China. Research carried out by Gauto et al. [33] resulted in average value of 115.3 kgCO$_2$e/kWh for batteries produced in China. Tabrizi, Bonalumi and Lozza [39] estimate GHG emissions between 99 and 136 kgCO$_2$e/kWh for batteries produced in China, and battery production in Europe with the potential to reduce carbon intensity compared to China, with estimated emissions between 46,5 and 126,5 kgCO$_2$e/kWh for batteries produced in modern European factories. This paper adopts the high voltage battery impact factor of 110 kgCO$_2$e/kWh and 75 kgCO$_2$e/kWh for battery production in China and in Europe, respectively, according to Transport & Environment [21] and compatible with the references analyzed.

The adopted vehicle production intensity factors according to production site and vehicle configuration are resumed in Table 1. The vehicle body intensity factor for ICEV and HEV are considered the same assuming the HEV is equipped with all components of ICEV plus electric powertrain.

Table 1. Vehicle production intensity factors [23].

Production site		BR	EU	CN
Electricity intensity	[gCO$_2$e/MJ]	27,7	89,7	190,3
Vehicle body ICEV / HEV	[kgCO$_2$e/kg]	1,5	4,8	10,2
Vehicle body BEV	[kgCO$_2$e/kg]	1,3	4,3	9,1
High voltage battery	[kgCO$_2$e/kWh]	-	75	110

Total GHG emitted during vehicle production are calculated in Table 2 according to vehicle category, powertrain, technical specifications and production site. Despite the preponderance of China in terms of production capacity for high voltage batteries of electrified vehicles, concentrating around 77% of global capacity pointed by Sun et al. [40], this study adopts a lower intensity BEV with vehicle and battery produced in EU and a higher intensity BEV produced in China. The HEV production impact consider only the worst case with battery, with considerable lower capacity in this application, produced in China. The logistics impact complexity is out of this study's scope and it's not considered in these simulations.

Table 2. Production impact, [1][41], [2][42].

	Vehicle		Production		
	body	battery	site		GHG
	[kg]	[kWh]	body	battery	[tCO$_2$e]
L_{ICEV}	1405	-	BR	-	2,1
L_{HEV}	1398	1,3	BR	CN	2,1
SC_{ICEV}	818	-	BR	-	1,2
SC_{BEV}	789	26,8	EU	EU	5,4
SC_{BEV}	789	26,8	CN	CN	10,1
SUV_{ICEV}	1684	-	BR	-	2,5
SUV_{BEV}	1688	78,0	EU	EU	13,1
SUV_{BEV}	1688	78,0	CN	CN	23,9

VEHICLE DRIVING – The analysis of the driving phase traditionally considers the vehicle's energy efficiency in the combined cycle, also used in Brazil (NBR7024) [9]. The Brazilian Vehicle Labeling Program (INMETRO) [43] provides, in addition to the energy consumption value in the combined cycle measured inside the emissions laboratory, the adjusted autonomy values, more representative of real use conditions, for urban and highway cycles. The measurements carried out in the laboratory can be corrected to better reproduce the values close to those found by users in real use conditions that involve: weather variation, track slope, driver behavior, energy regeneration strategies and other factors that are not observed inside the laboratory (BURTON et al. [44]). The Brazilian Ordinance 377 regulation (INMETRO, [45]) determines specific correction factors for urban or highway cycle, applicable to ICEVs and HEVs. The correction factor for BEVs, the same for urban and highway cycles for these applications, is determined by the Brazilian Ordinance 169 (INMETRO, [46]). The division of the fuel energy density, 28,99 MJ/dm^3 for E22 (INMETRO, [47]), by the vehicle corrected autonomy (INMETRO, [43]) results in the corrected energy consumption in Table 3, in urban (City) and highway (Hwy) cycles. Table 3 confirms the higher efficiency of ICEVs in highway and the higher efficiency of electrified vehicles in urban cycle.

Table 3. Vehicle corrected energy efficiency [23].

Vehicle		City [MJ/km]	Hwy [MJ/km]
SC	ICEV	1,95	1,86
	BEV	0,55	0,73
L	ICEV	2,50	2,09
	HEV	1,78	2,00
SUV	ICEV	3,05	2,45
	BEV	0,99	1,16

The different properties of reference fuels in Brazil (E22 and E100) affect the energy and exergy efficiencies of vehicles in the Brazilian scenario. Azhaganathan and Bragadeshwaran [48] point that the efficiency of ICEVs increases with the increase of ethanol concentration in the fuel blend. According to Rovai and Mady [49], the difference in engine efficiency between E22 and E100 observed in stabilized condition, 1.5% higher with E100 in absolute values under the condition of maximum engine efficiency, is beyond the scope of this work. Therefore, this study assumes the same engine efficiency for any fuel blend.

Since the establishment of the National Alcohol Program (BRASIL, [50]), widely known as PROALCOOL, Brazil has had the option of two fuels for spark ignition (SI) engines at gas stations, currently: gasoline (E27) since 2015 (MAPA, [51]) or hydrous ethanol (E100). Considering that all the E27 and E100 sold to the final consumer in Brazil are used by light vehicles equipped with SI engines, and that this volume totals approximately 57500 billion liters per year between 2017 and 2021, it is estimated that light vehicles in Brazil used, on average, the E50 mixture in this period according to Rovai, Seixas and Mady [23]. Other authors, such as Mera et al. (2023) [52], also consider that ethanol represents around half of the volume of fuel consumed by the Brazilian passenger car fleet. The driving GHG emissions along conventional urban and highway cycles are calculated by multiplying vehicle energy efficiency (Table 3) by the energy intensity of each energy source, the Brazilian electricity for BEVs or fuel blends, with 22% (E22), 50% E50) and 100% ethanol v/v (E100), in Table 4 for ICEVs and HEV.

Table 4. Energy sources WTW in Brazil [23].

	Electricity	E22	E50	E100
WTW [gCO$_2$e/MJ]	27,7	78,2	64,2	28,2

The extensive study carried out by Cui et al. [53] about the use of BEVs in China, more specifically in Beijing but would be applied to any large cities due to similarity, indicates that the majority of users travel two trips a day, probably to and from work. Still according to Cui et al. [53] BEVs for private use travel an average of 33 km per day, with approximately 25% of the fleet traveling up to 20 km/day, which reinforces the importance of this low usage analysis. Faria, Baptista and Farias [54] analyzed vehicles used in urban routes totaling between 712 and 1418 km per year, which would represent routes of 1,0 to 1,9 km. Amatuni et al. [55] analyzes the effects of car sharing on GHG, in which one of its effects is the reduction in the annual mileage of private cars, a phenomenon that highlights the importance of analyzing short trips. In one of the scenarios studied, referring to the North American city of San Francisco, the annual use of private cars was reduced from 9774 to 4451 km/year, which represents approximately two daily journeys of 6 km.

The cold phase impact on vehicle energetic efficiency can be determined by the usage factor (FU) from the mathematical model proposed by Rovai [10], illustrated in Figure 1. This model were developed based on a compact sport utility vehicle driven on urban cycle NBR6601 [7]. The urban test begins with a cold start, between 20 and 30 ºC, followed by a warmup along the test cycle. During this period the vehicle fuel consumption should be multiplied by FU which represents the impact of cold phase phenomena represented by: engine friction in function of lubricant temperature, catalytic converter light off strategy and the warmup of engine hardware. As can be observed in Figure 1, the FU reaches close to 1 value after 10 km driven, demonstrating the cold phase effects are significant only below 10 km driven. The FU is mathematically defined by the dotted line that represents the adjusted fuel consumption experimentally determined. The dotted line in the detail of Figure 1, plotted in logarithmic scale, overestimates the FU between 100 and 1000 m travelled, which represents a conservative FU value enhancing cold phase impacts.

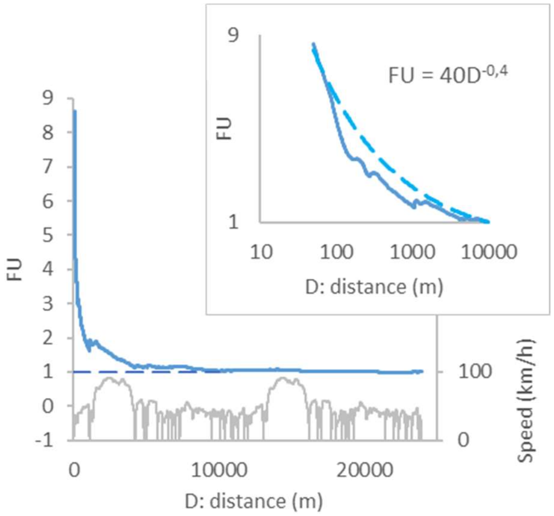

Figure 1. Cold start factor (FU) impact on fuel consumption, adapted from [10].

The FU is determined by Equation 1 and valid between 50 and 10000 m travelled distance.

$$FU = 40 \cdot D^{-0,4} \qquad (Eq.1)$$

FU = usage factor, energetic efficiency multiplier,

D = distance travelled in a trip (m).

It is assumed that the low usage urban cycles affect the fuel consumption of ICEVs and HEVs, both equipped with internal combustion engines. These specific use can be represented by equidistant daily routes, to and from the destination, always starting with a cold start. In this way, routes of 1 to 10 km result in journeys between 2 and 20 km per day, accumulating 730 to 7300 km per year, which requires this specific assessment. The drive cycles between 1 and 10 km, the fuel consumption of ICEVs and HEV in urban cycle can be corrected by multiplying the urban values (City, Table 3) by FU (Equation 1), in Table 5.

Table 5. FU in terms of distance travelled.

D [km/drive cycle]	FU	2·D [km/day]	2·D·365 [km/year]
1	2,52	2	730
2	1,91	4	1460
3	1,63	6	2190
4	1,45	8	2920
5	1,33	10	3650
6	1,23	12	4380
7	1,16	14	5110
8	1,10	16	5840
9	1,05	18	6570
10	1,005	20	7300
15	1,00	30	10950
21,9	1,00	44	16000

BEVs do not present a significant variation in efficiency during cold start and warm-up between 20 and 30°C of NBR6601 [7]. According to Skuza, Jurecki and Szumska [16] and Mamarikas et al. [17] traffic conditions represent the biggest impacts on BEV consumption. Al-Wreikat, Serrano and Sodré [56] pointed out an increase in consumption in BEVs at low temperatures, but discarding significant variations at moderate temperatures, between 15 and 25 °C.

The vehicle maintenance throughout the driving period should also be considered when calculating GHG emissions. In addition to maintenance related to wear parts, the durability of the high-voltage battery of electrified vehicles and its eventual replacement during the vehicle useful life must be assessed. The GHG from maintenance of wear parts over 200000 km use, without the need to change the high voltage battery, can be estimated based on data from other publications. Considering the work of Kawamoto et al. [57] the impact of vehicle maintenance on GHG emissions is estimated at about 0,6 tCO_2e for ICEV and about 0,5 tCO_2e for BEV, resulting in 0,1 tCO_2e difference between ICEV and BEV. The same estimative from Bieker [20] results in emissions of 1,0 tCO_2e for the maintenance of the ICEV and 0,8 tCO_2e for the BEV, a difference of 0,2 tCO_2e. According to Mera et al. [52] the difference in the maintenance carbon footprint between ICEV and BEV reaches 0,25 tCO_2e, with 1,0 tCO_2e being emitted for the ICEV and 0,75 tCO_2e for the BEV. According to Van Mierlo, Messagie and Rangaraju [58] fast recharging can significantly reduce the useful life of high voltage batteries, requiring more than one battery to cover 200000 km. De Oliveira Gonçalves et al. [59] estimate battery durability at 550 recharge cycles, which varies from 82500 to 246400 km, depending on the autonomy of the vehicles analyzed. Adopting this maximum value of 550 battery recharge cycles would result, approximately, in durability of 156000 to 175000 km, for SUV_{BEV} and SC_{BEV} considered respectively of this study, for urban cycle (Table 3) and nominal charging capacity of the battery (Table 2). Ortolan et al. [60] admit battery durability of 150000 km. Pipitone, Caltabellotta and Occhipinti [24] consider the warranty limit of 160000 km as battery durability, the same period adopted by Kawamoto et al. [57] which takes into account battery replacement at this mileage. Mera et al. [52] estimate battery durability between 600000 and 1200000 km. It is important to highlight that the warranty offered by manufacturers for electrified vehicles is limited to 160000 km or 8 years in Brazil. However, an interesting result about the durability of BEVs in Brazil was published by Revista Quatro Rodas [61], reporting that a commercial vehicle used for deliveries on urban routes was the first BEV to reach 290000 km in Brazil over six years operation without deep maintenance. During this period, battery degradation resulted in a range reduction from an initial 250 km to 210 km per full charge at the end of the test, but still considered appropriate for use. On the contrary, conventional ICEVs usually complete 200000 km when preventive maintenance is adequately performed. These results indicate that, as in conventional vehicles (ICEVs), the durability of the high voltage battery may exceed the warranty period. Vehicle maintenance was not considered in the calculations, neither any replacement of the high-voltage battery in electrified vehicles taken into account.

VEHICLE RECYCLING – Vehicle recycling is the last step in analyzing the carbon footprint by LCA. However, the methodologies for estimating CO_2e emissions at this stage are not yet as consolidated as those adopted in two previous phases.

Ellingsen, Singh, and Stromman [18] consider the end of life (EOL) impact for vehicles and batteries from public inventories. The conclusions indicate that batteries affect the GHG emissions of electrified vehicles, but both ICEV and BEV have a similar EOL impact. However, the impact on the recycling stage, for any of the configurations analyzed, is much less significant than the previous stages of production and use, also pointed out by Egeskog et al. [27] and Evrard et al. [28]. Furthermore, the reduced number of BEV batteries in the recycling stage in 2020, according to Transport & Environment [21], results in pilot battery recycling projects that do not guarantee reliable values for their estimation. This uncertainty in the estimation for the recycling stage is expected to be reduced significantly in the coming years. Pipitone, Caltabellotta and Occhipinti [24] conducted studies to estimate the impact of battery recycling based on available literature on European processes, in addition to using the GREET mathematical model from Argonne National Laboratory [62] to calculate the recycling impact of vehicle body. Battery recycling showed a significant difference between vehicle configurations, resulting in less than 2,5% of GHG emissions since the production up to 150000 km of vehicle use. Buberger et al. [19] analyzed recycling impact coefficients for a specific vehicle and concluded that, even when batteries are effectively recycled, ICEV and BEV result in similar emissions at the recycling stage. For Bieker [20], recycling batteries will probably significantly reduce the impact of production, but due to the uncertainty surrounding recycling processes these GHG credits are not considered. Mera et al. [52] also don't take battery recycling into account. Another important consideration regarding the feasibility of extending the period of use concerns the possibility of extending battery life in stationary energy accumulators, which demand less battery capacity compared to vehicular use. Onat, Kucukvar and Tatari [63] consider the recycling stage to be insignificant compared to the other stages of the life cycle, and is therefore ignored. Ellingsen, Singh and Stromman [18] estimate that the recycling step can reduce GHG emissions from 0,7 tCO_2e for ICEV to 0,9 tCO_2e for BEV, which means only 0,2 tCO_2e difference from electrification. De Souza et al. [64] reach limited values for the environmental contribution of recycling, less than 1% of emissions throughout the life cycle. Low emissions value relative to the recycling stage calculated by Kawamoto et al. [57], approximately 65 kgCO_2e, is considered negligible too.

Literature review shows an insignificant impact of the recycling stage compared to previous stages of the life cycle, and a similar impact of recycling can also be considered for any vehicle configurations in this study: ICEV, HEV and BEV. The main objective of this study is to quantify and compare the LCA of different technologies and, given the uncertainties and the minor impact of EOL on the LCA, the carbon footprint of the recycling stage was not considered.

RESULTS AND DISCUSSION

The GHG breakeven is the vehicle mileage required to start mitigating greenhouse emissions when replacing ICEVs by electrified versions, HEVs or BEVs. For this analysis in which daily use determines the accumulated mileage along year, the breakeven can be already calculated as a function of period of use, e.g. in years of use. The GHG breakeven simulations performed by Rovai, Seixas and Mady [23] concluded that urban cycle are more effective than highway to reduce GHG emissions by vehicle electrification. Additionally, the cold phase should finish shortly in highway due to higher engine speed and load compared to urban cycle, besides that short highway trips don't make sense. So, the simulations in this study were performed only in urban cycle. The urban simulations performed consider the same FU for ICEV and HEV because in these applications, according to Al-Wreikat, Serrano and Sodré [56] and Mamarikas et al. [17], it is estimated that the gains arising from the operation of HEVs in electric mode on urban routes exceed the impacts of the lower average lubricant temperature during HEV cold phase observed by Tomanik, Tomanik and Morais [65]. This premise guarantees more conservative results. The simulations were performed with ICEVs and HEV running on E22, E50 or E100. Besides, the curves in Figures 2 to 6 show numerical values only for E50 and E100 demonstrating the decarbonization potential of improving the ethanol content in fuel blend from current average fuel blend (E50) to E100 in Brazil. The E22 curves were plotted in dotted lines to demonstrate its closest results to E50.

ICEV x HEV – The analysis of the decarbonization regarding the replacement of an ICEV by a HEV were performed for a large car (L) that offers these both powertrain options produced in Brazil.

Large vehicle (L) – Figure 2 illustrates the period, in years, as a function of vehicle daily use, in km/day, to achieve environmental compensation in terms of carbon footprint simulating the replacement of the L_{ICEV} by the L_{HEV} from lower to higher intense urban use. Even in this specific and challenging low usage condition, the L_{HEV} proves interesting with breakeven of less than two years over L_{ICEV} with E50. Also in the most critical condition for breakeven, when ICEV uses E100 in Brazil over very short journeys, the compensation occurs before four years of use, in about the middle of the warranty period of electrification system. In case of more intense use the breakeven of a L_{HEV} is almost immediate, during the first year of use.

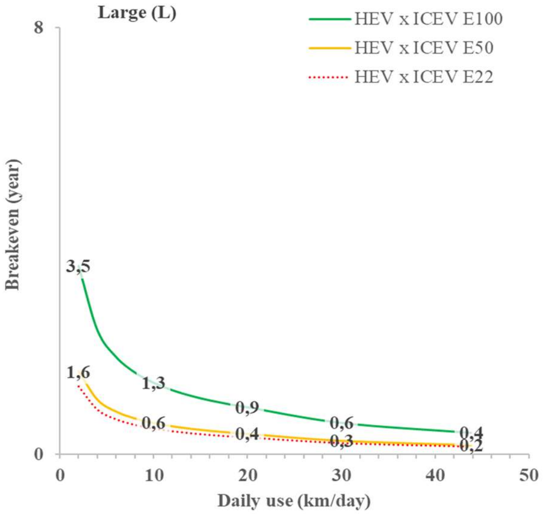

Figure 2. Breakeven of L_{ICEV} x L_{HEV}.

ICEV x BEV – The breakeven analysis considering the replacement of an ICEV by a BEV were simulated for a subcompact and a sport utility cars. In order to better compare the extreme categories and realize the influence of vehicle size on decarbonization, Figures 3 to 6 were plotted in the same scale, up to 150 years. The BEVs currently available in Brazil are still imported, and the lower impact to produce the electric vehicle and the high voltage battery can be considered for production in Europe (EU) compared to a higher impact if produced in China (CN).

Subcompact vehicle (SC) – Figure 3 shows the breakeven simulation results when replacing a SC_{ICEV} by a SC_{BEV} produced in EU. For the current scenario in which SC_{ICEV} runs on E50 it is necessary more than 10 km/day to achieve the breakeven before electrified system warranty expires. In extreme condition the breakeven could demand more than 19 years. The use of E100 on SC_{ICEV} could postpone the breakeven to the boundary of for more than 46 years, unlikely. The 10 km/day use of SC_{ICEV} with E100 increase de breakeven from about 8 to practically 20 years. For the low usage condition, below 20 km/day, in which the cold phase affects ICEV efficiency, the breakeven of SC_{BEV} over SC_{ICEV} with E100 demands more than 14 years, 6 years over BEV warranty limit. The breakeven of SC_{BEV} versus a SC_{ICEV} running on E100 would occur during BEV warranty for driving more than 30 km/day.

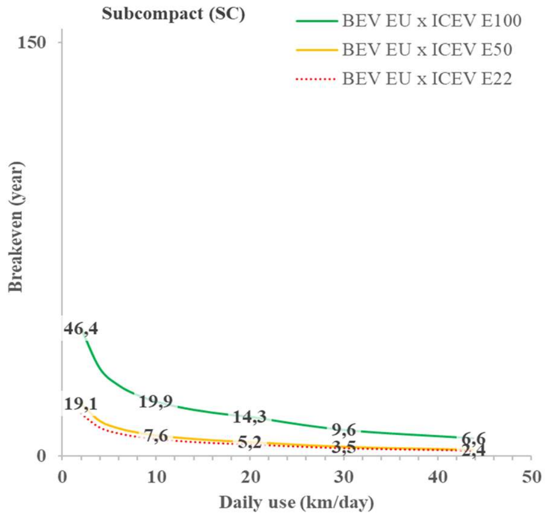

Figure 3. Breakeven of SC_{ICEV} x SC_{BEV} from EU.

This analysis for SC_{BEV} produced in China, in Figure 4, results in breakeven periods 113% higher than the values calculated for SC_{BEV} produced in EU (Figure 2). The SC_{ICEV} using E50 imposes more than 40 years in extreme low usage and about 30 km/day to achieve the breakeven during BEV warranty. Breakeven values moves to the extreme of up 99 years with SC_{ICEV} using E100, demanding 14 years for a vehicle running 44 km/day or 16000 km/year.

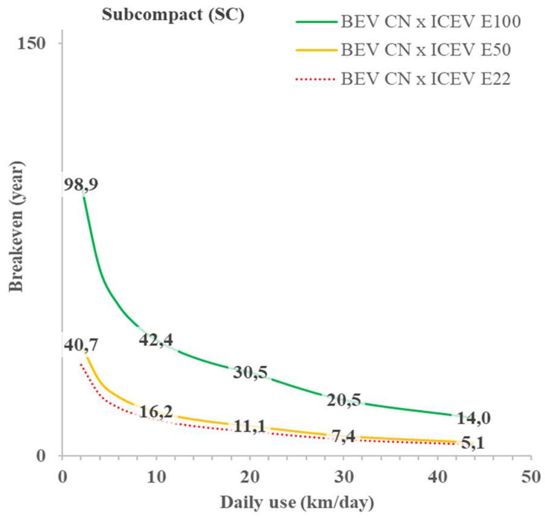

Figure 4. Breakeven of SC_{ICEV} x SC_{BEV} from CN.

Sport utility vehicle (SUV) – Similar analysis were performed for the sport utility vehicle, less favorable than the SC for decarbonization, but very significant in sales, increasing market share in the last decade in Brazil. The breakeven of a SUV_{BEV} is more than 60% higher than the one for SC_{BEV} both made in EU (Figures 3 and 5). In Figure 5, the decarbonization by replacing a SUV_{ICEV} with E50 by a SUV_{BEV} from EU reaches more than 31 years in lowest simulated usage and demands more than 20 km/day for the breakeven before the 8 years of BEV warranty limit. The SUV_{ICEV} with E100 increases the breakeven to more than 76 years in the worst case and more than 11 years running more than 44 km/day, or 16000 km/year.

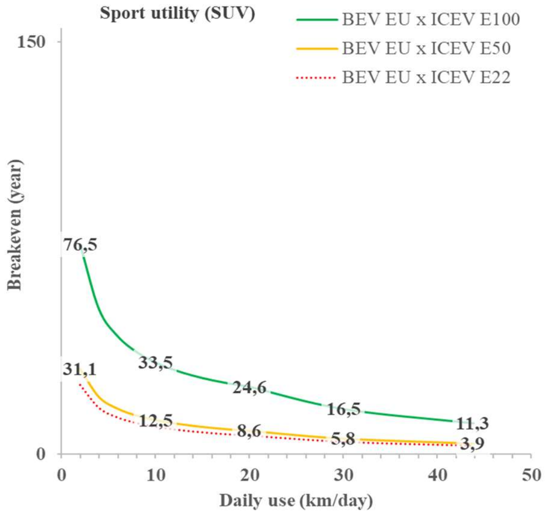

Figure 5. Breakeven of SUV_{ICEV} x SUV_{BEV} from EU.

The SUV_{BEV} produced in China (Figure 6) results in breakeven 102% higher than the periods calculated for SUV_{BEV} produced in EU (Figure 5). The SUV_{BEV} from CN demands breakeven more than 55% higher than the breakeven of SC_{BEV} from CN, little lower than the comparison with vehicles from EU but still a considerable impact that depends on customer decision. The results in Figure 6 comparing the SUV_{BEV} from CN with SUV_{ICEV} running on E50 varies from 63 years for lowest usage to 8 year, exactly the warranty limit, for 44 km/day or 16000 km/year. The option of E100 in SUV_{ICEV} increases the breakeven to more than 150 years for an extremely 2 km/day use, reducing to a considerable great period of about 23 years for 44 km/day which means16000 km/year.

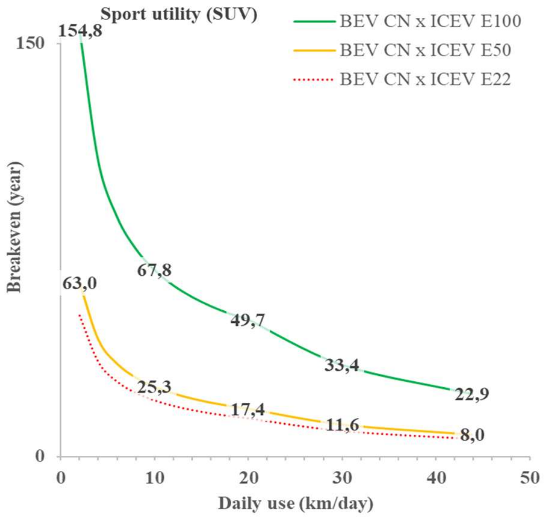

Figure 6. Breakeven of SUV_{ICEV} x SUV_{BEV} from CN.

CONCLUSIONS

In general, the results indicated that the electrification of the fleet for low urban use through HEV results in GHG emissions reduction in a period of less than four years, which increases the probability of its occurrence. The HEV running on E100 is the fastest electrification option considered in this study for decarbonization. The electrification through BEVs replacing the ICEVs running on E50 appears to be feasible, with breakeven during the 8 years warranty limit of electrified systems, for subcompact vehicle if the SC_{BEV}, produced in Europe, travel at least 10 km/day in Brazil. Similar result is achieved running more than 30 km/day in Brazil for SC_{BEV} made in China. For larger vehicles (SUV), the replacement of ICEVs by BEVs is achieved during 8 years warranty of BEVs when driving more than 20 km/day with a SUV_{BEV} from EU, or more than 44 km/day with a SUV_{BEV} from CN. In case of ICEVs using E100 the SC_{BEV} from EU became effective in decarbonization when driven by more than 30 km/day, three times the mileage defined with E50. The other options, SC_{BEV} from CN or SUV_{BEV} from EU or CN, would demand higher daily usage, more than 44 km/day or more than 16000 km/year to be accomplished before 8 years of use. The use of E100 practically eliminates the possibility of fleet decarbonization by BEVs in low intensity use, remaining this possibility for high usage vehicles like car sharing. The vehicle category is also a significant variable for decarbonization. In general the customer option by SUVs instead of SCs demands from 55 to 60% higher mileage for breakeven. The currently imported BEVs available in Brazil have the breakeven period increased in 113% for SC_{BEV} or in 100% for SUV_{BEV} imported from China instead of Europe.

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DEFINITIONS / ABBREVIATIONS

ABNT	Brazilian association of technical standards
BEV	battery electric vehicle
CN	China
CO_2e	equivalent carbon dioxide
D	distance travelled in a trip (m)
E22	reference gasoline in Brazil with 22% v/v of ethanol

E50	average fuel with 50% v/v of ethanol for SI engines in Brazil
E100	Brazilian hydrous ethanol
EEA	European environment agency
EOL	end of life, recycling
EPE	Brazilian energy research company
EU	Europe
FU	usage factor, energetic efficiency multiplier
GHG	greenhouse gas emissions
HEV	full hybrid vehicle (not plugin)
ICEV	internal combustion engine vehicle
IEA	international energy agency
INMETRO	Brazilian metrology institute
L	large vehicle
LCA	life cycle assessment
PROCONVE	Brazilian vehicle emissions control program
SC	subcompact vehicle
SUV	sport utility vehicle
WTW	well-to-wheel carbon intensity