RETURN ON ENERGY INVESTMENT OF COMBUSTION, ELECTRIC AND HYBRID VEHICLES IN BRAZIL

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Overview

The effort to reduce the fossil fuel usage is forcing the transport sector to pursuit new alternatives. Brazilian transport sector is highly dependent on liquid fossil fuels causing economic and environmental issues. In this study, new technologies regarding vehicles, such as the Hybrid Electric Vehicle (HEV) and the Battery Electric Vehicle (BEV), and renewable fuels, such as ethanol, had their performance evaluated by the Life Cycle Assessment technique. The analysis was divided in two main areas: the use phase (which included the primary energy expenditures of the fuels' and electricity's life cycle) and the one correspondent to the vehicle's manufacture, maintenance and disposal. Energy "cash flows" were calculated for each option with an initial energy expenditure assigned to year zero, constant expenditures along the use phase and a final one for the vehicle disposal. With the energy "cash flows" of each option, incremental flows were obtained for comparisons between two options, in order to evaluate a net energy saving. If the Net Present Energy Value of this incremental flow was positive, so was the energy savings and the substitution is worthy in terms of energy. Different social discount rates were considered in the analysis to assess the behavior of the energy savings when their values are differentiated in time. After the pairwise comparisons, the options were ranked according to the consumption of primary fossil energy: HEV (Ethanol), FLEX (Ethanol), BEV, HEV (Gasoline) e FLEX (Gasoline). Among the main technologies that have been considered to reduce the primary fossil fuel consumption in the transport sector, the HEV using ethanol was the best option under the conditions assumed in this study. In order to improve even further its net energy savings, investments aimed at the reduction of the energy consumption in the vehicle manufacture are recommended.

Keywords: Life Cycle Assessment, Primary Fossil Energy, Fossil Fuels, Hybrid Electric Vehicle, Battery Electric Vehicle, Flex Vehicle, Social Discount Rate.

1. Introduction

The concern about the fossil fuel usage has been increasing in the past years given its implications on economic, environmental and political issues. It is well known that the increase in the average global temperature has an anthropic cause (IPCC, 2013), pushed by the non-renewable energy use, mainly fossil fuels. Besides global impacts, their use also influences local elements such as air quality having an implication in public health and the population well-being. Fossil fuels have multiple uses, but one that is extremely relevant is transport. In 2013, 83.1% of the energy used in the Brazilian transport sector corresponded to fossil sources (EPE, 2014). Even though the country produces virtually all the crude oil it demands, importation is still needed given the technical features of the national refineries. From 2004 to 2013, 21.2% of the crude oil processed was imported (EPE, 2014). Besides that, in 2008 Brazil became an importer of oil products, reaching an imported share of 19.2% in 2013 (EPE, 2014). This behavior is linked to the fact that the Brazilian private fleet presented a significant growth in the past years. According to the number of vehicles in Brazil (DENATRAN, 2000, 2010) and Brazil`s population (IBGE, 2003, 2011), from 2000 to 2010 the vehicle per habitant index went from 0.11 to 0.19, what means that the number of private vehicles grew above the population`s growth. The projections for the fleet growth and the fuel consumption shows that the trend observed in the last decade will continue and as the number of vehicles will increase, so will the fuel consumption. In this scenario it is imperative a technical and political discussion aimed at the reduction of fossil energy consumption in the transport sector. Examples of alternatives that fulfill this requirement are the hybrid and electric vehicles, as well as the utilization of biofuels such as ethanol. However, even though these alternatives present a good efficiency in the use phase, the higher energy investment required for their manufacture may turn a supposed advantage in a disadvantage. This work evaluated the return on primary energy investment of these alternatives, considering their overall capacities of reducing the primary fossil energy consumption.

2. Methodology

This study selected three technology options that are relevant in the present and are most likely to be adopted in the Brazilian context: Conventional Flex Vehicle (FLEX), bi-fuel Hybrid Vehicle (HEV) and Battery Electric Vehicle (BEV). The first one is already a reality in Brazil but the other two have an almost zero presence in the national fleet although they are a reality in markets such as the North American and the European. In order to compare different technologies that have the same objective (mobility) regarding their primary fossil fuel consumptions, the appropriate methodology is the Life Cycle Assessment (LCA). In a proper analysis of the primary fossil energy usage of each option it is indispensable to assess its whole life cycle. The differences in energy expenditures in the vehicle manufacturing, maintenance and disposal may produce different conclusions in comparison to an analysis that only studies the use phase. But not only the vehicle itself has a life cycle, the liquid fuel used (Ethanol and Gasoline C) and the electricity also have their production chain which must be assessed with the LCA technique as well.

First, it was gathered data for the three options regarding their energy expenditures that are independent of their use (manufacture and disposal) and the ones that are (energy consumption per kilometer). Combining the data of the use dependent expenditures with the use independent expenditures, it was possible to obtain the final primary energy balance of each individual transportation option.

2.1 – Vehicle manufacture, maintenance and disposal

The data correspondent to the vehicle manufacture, maintenance and disposal was obtained in (GREET, 2015). Unfortunately, specific Brazilian data was not public available, so it could not be used in this study. The data refer to the primary fossil energy consumption in the manufacture, maintenance and disposal of the vehicles for the United States context. Table 1 summarizes the used information:

Table 1: Primary energy consumption in vehicle manufacture, maintenance and disposal in MJ

	Manufacture and maintenance (MJ)	Disposal (MJ)
FLEX	90641	2923
HEV	95902	2923
BEV	112664	2923

GREET (2015)

2.2 - Fuel use

Since data was gathered from different sources, they should refer to a similar vehicle to respect a comparability criterion. The vehicles were selected among the same category (similar weights, same use and similar performances) despite the different technologies used. For the HEV, JRC (2013) presented its data for a generic C-segment Sedan passenger vehicle, for the BEV, it was used the data presented in GREET (2015). The Brazilian Conventional Flex Fuel vehicle was selected among the options that matched the specifications provided in JRC (2013) and GREET (2015).

An adequate choice for the Brazilian Conventional Flex Fuel vehicle was the Toyota Corolla GLI 1.8-16V CVT. Its weight, maximum power and torque are close to the specified in GREET (2015) and JRC (2013). It is important to state that the selected vehicle is not representative choice of the Brazilian fleet and it was chosen to avoid the distortion that a different category comparison would produce.

Fuel economy data for the Toyota Corolla was obtained in the Brazilian Labeling Program (INMETRO, 2016) while for the BEV in GREET (2015) and for the HEV in JRC (2013). The consumption of each technology is summarized in Table 2:

Table 2: Fuel economy

	Gasoline C	Ethanol	Electricity
	km/l	km/l	Wh/km
FLEX	12.00	8.27	NA*
HEV	21.45	14.84	NA*
BEV	NA*	NA*	184.33

*NA – Not Applicable. INMETRO (2016), JRC (2013) and GREET (2015).

The values from the HEV and the FLEX were obtained from two different tests: the Brazilian data from INMETRO based on the Brazilian adopted drive cycle (NBR-7024), while the European data according to Europe`s adopted drive cycle (NEDC – New European Drive Cycle). In order to reduce this difference, the Brazilian results were adapted by calculating a new consumption by multiplying the relative time spent on the NEDC in an urban and extra-urban use by the consumptions obtained by INMETRO. Also, the HEV data from JRC (2013) refer to the fuel blends E20 and E85. E20 was considered very close to E22 (used in Brazil), so it was used as published. For E85, energy equivalence with hydrated ethanol was assumed in order to estimate the volume equivalence of 1 liter of E85. The BEV value was used as published in GREET (2015).

In order to complete the life cycle of each transportation option, the primary fossil fuel expenditures on electricity generation and production of the liquid fuels were estimated based on information from the literature and EcoInvent v.3 Database. Electricity generation data in Brazil was readily available in the Ecoinvent database, while sugarcane ethanol life cycle performance was available in SEABRA et al. (2011). The estimations for the fossil liquid fuels, on the other hand, were more laborious. In 2003, PETROBRAS published a report regarding the crude oil exploration and production, refining and distribution in Brazil during the 1990-2002 period (PETROBRAS, 2003). It contains data of the energy expenditures that are required to perform those activities. The objective of the following calculation was to obtain the primary fossil energy required in order to provide 1 MJ of liquid fuel to the market. A different treatment for the four steps of the production chain was developed.

2.2.1 - Petroleum Liquid Fuels Production Chain

The production chain is divided in four steps: Exploration and Production, Refining, Transport and Distribution. At each step the ratio between the primary energy that enters that process and the energy that leaves it was calculated. The numerator is always in a primary energy basis. The energy inputs that are external to the process (e.g: electricity purchased from the grid) were corrected to their primary energy equivalents using multiplying factors obtained in the literature for E&P and Refining steps, shown in Table 3. For the Transport and Distribution steps the values were corrected using the intermediary results obtained internally in the LCA modeling. Energy flows that are internal to the processes are corrected to the primary energy equivalent using the Ein/Eout ratio from the last process. By doing so, at the last step of the production chain a global Ein/Eout ratio is obtained relating the primary energy required at the primary energy source to provide 1 MJ of liquid fuels to the final consumer.

Table 3: Primary equivalent conversion factors from the literature

	Natural Gas	Diesel/Fuel Oil*	Electricity
Factor	1.18	1.20	0.44

*It was considered that the Fuel Oil Factor was the same as the Diesel. (JRC, 2014) and EcoInvent v.3

Figure 1 presents an overview of the modeled production chain of the liquid fuels:

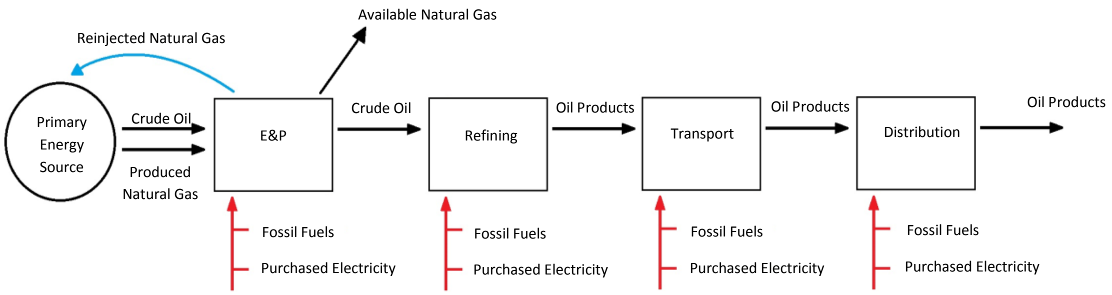

Fig 1: Oil products production chain

2.2.1.1 - Exploration and Production (E&P)

This activity consumes natural gas, fossil fuels and electricity and produces crude oil and natural gas. Purchased electricity and fossil fuels are obtained externally to this process, so their values were corrected to its primary energy equivalent according to Table 3 factors.

As can be seen in Figure 1, E&P step involves the production of crude oil and natural gas from the Primary Energy Source. A possibility to enhance the crude oil production consists in the reinjection of the produced natural gas in the primary energy source in order to increase the oil recovery. Since this energy is not consumed and probably the reinjected gas will be produced again at some point, it was not considered as an energy expenditure. Energy consumption of this phase is related to the many processes that this activity requires such as pumping, separation processes, gas cleaning, water treatment, electricity generation among others. The available natural gas, which is the share that will be commercialized, is the produced share decreased from the reinjected share, the consumed and the burnt in flaring. The ratio between the primary energy that enters this step and the energy that leaves it is given by Equation 1:

$$\left(\frac{E_{in}}{E_{out}}\right)_I = \frac{Crude\ Oil_{PES} + NG_{produced} - NG_{reinjected} + Fossil\ Fuels_{prim.eq} + Electricity_{prim.eq}}{Crude\ Oil + NG_{available}} \quad (1)$$

$X_{prim.eq}$ – Energy in its primary energy equivalent.

The ratio $\left(\frac{E_{in}}{E_{out}}\right)_I$ represents the energy expended from the primary energy source to provide 1MJ of crude oil and natural gas at the production site.

$Crude\ Oil_{PES}$ – Crude oil directly from the Primary Energy Source.

2.2.1.2 – Refining

In Refining, the crude oil enters the process and oil products leave it. To obtain the products energy must be expended. According to PETROBRAS (2003), the refineries consume fossil fuels and electricity purchased from the grid. It was considered that all the fossil fuels are obtained within the process except the natural gas which is obtained externally. The refining step is shown in Figure 1.

The ratio between the primary energy that enters this step and the energy that leaves it is given by Equation 2:

$$\left(\frac{E_{in}}{E_{out}}\right)_{II} = \frac{Crude\ Oil * \left(\frac{E_{in}}{E_{out}}\right)_I + NG_{prim.eq} + Electricity_{prim.eq}}{Oil\ Products} \quad (2)$$

The ratio $\left(\frac{E_{in}}{E_{out}}\right)_{II}$ represents the energy expended from the primary energy source to provide 1MJ of oil products at the refinery.

2.2.1.3 – Transport and Distribution:

The Transport step is responsible for the oil products and crude oil transportation and Distribution step is responsible for delivering the oil products to the final consumers. Their energy uses comprehend fossil fuels such as diesel, fuel oil and gasoline among others and electricity purchased from the grid. The Transport and Distribution Steps are shown in Figure 1.

In these processes more than one product is being transported, so it is not possible to calculate the exact amount of energy that enters it since what is being transported is not specified in PETROBRAS (2003). To contour this, it was adopted that the Transport and Distribution steps are delivering a generic oil product that has the same lower heating value and density as the crude oil considered in this study. The ratio between the primary energy that enters these steps and the energy that leaves them is given by Equation 3 for Transport Step and by equation 4 for Distribution Step:

$$\left(\frac{E_{in}}{E_{out}}\right)_{III} = \frac{generic\ Oil\ Product * \left(\frac{E_{in}}{E_{out}}\right)_{II} + mass.\left(\frac{Energy_{prim.eq}}{t}\right)}{generic\ Oil\ Product} \quad (3)$$

$$\left(\frac{E_{in}}{E_{out}}\right)_{IV} = \frac{generic\ Oil\ Product * \left(\frac{E_{in}}{E_{out}}\right)_{III} + mass.\left(\frac{Energy_{prim.eq}}{t}\right)}{generic\ Oil\ Product} \quad (4)$$

$\left(\frac{Energy_{prim.eq}}{t}\right)$ – This value represents the fossil fuels and the electricity in their primary energy equivalents consumed per ton of the generic oil product transported.

$mass$ – Is the amount of tons of the generic oil product being transported.

The ratio $\left(\frac{E_{in}}{E_{out}}\right)_{III}$ represents the energy expended from the primary energy source to provide 1MJ of generic oil products at the distribution base.

The ratio $\left(\frac{E_{in}}{E_{out}}\right)_{IV}$ represents the energy expended from the primary energy source to provide 1MJ of generic oil products to the market.

2.2.1.4 – Primary energy consumption for fossil liquid fuels

After carrying out the calculation according to what was presented above and using PETROBRAS (2003) as the main source of data, the ratio between how much primary fossil energy must be "invested" in order to obtain 1MJ of liquid fuels was obtained. The final value $\left(\frac{E_{in}}{E_{out}}\right)_{IV}$ is 1.16 MJ/MJ.

2.2.2 – Ethanol Production Chain

Data regarding the sugar cane ethanol was readily available in the literature. The amount of fossil fuels in a primary energy equivalence consumed in order to produce 1MJ of anhydrous ethanol was determined in SEABRA et al. (2011) as shown in Table 4:

Table 4: Sugarcane ethanol life cycle

	Primary Fossil Energy Use (MJ/MJ)
Sugarcane farming	0.088
Agr. Inputs production	0.040
Sugarcane transportation	0.019
Ethanol Production	0.004
Ethanol Transport and Distribution	0.022
Credits	
Electricity	-0.060
Bagasse	-0.033
Total WTW	0.080

SEABRA et al. (2011)

The study obtained by a well-to-wheels analysis an energy balance regarding the whole life cycle of the sugarcane ethanol, based in data collected from Brazilian mills in the 2008/2009 season. Given the fact that the study used a specific high quality data produced by CTC (Center of Sugarcane Technology) with a methodology coherent to what the present study assesses, it was chosen as a source for the sugarcane ethanol life cycle. In the present study, the energy expenditures of the production chain of hydrated ethanol and anhydrous ethanol were considered to be equal.

2.2.3 – Electricity Production Chain

EcoInvent v.3 Database presented the CED (Cumulative Energy Demand) of the Brazilian electricity generation mix, which is the demanded fossil energy accumulated throughout the generation facilities' life cycles divided by the their generation of electricity. The used value is 0.44. It is under 1, given the high participation of renewable sources in the national mix.

2.3 – Energy balance and energy "cash" flows

The general procedure to calculate the energy "cash" flows was: an initial energy consumption was assigned to year zero regarding the vehicle production and maintenance, followed by constant energy expenditures along the life cycle representing the use phase, and a final consumption related to the vehicle disposal. It was adopted a lifetime of 150000 km and an annual mileage of 10000 km. The comparison criterion was the Net Present Energy Value (NPEV), which is the Net Present Value (NPV) of the incremental energy "cash" flow of two options that are being compared. If NPEV is positive, the proposed substitution is worthy in terms of energy. Figure 2 shows a schematic representation of the incremental cash flow, for which NPEV is calculated according to Equation 5.

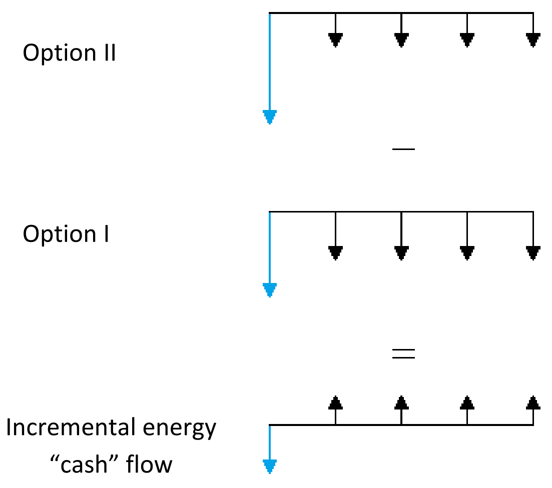

Fig 2: Schematic representation of NPEV calculation

$$NPEV = P + A\left[\frac{(1+i)^n-1}{(1+i)^n.i}\right] + \frac{D}{(1+i)^n} \quad (5)$$

$NPEV$-Net Present Energy Value in MJ.
P-Difference in the energy expended in year zero in MJ between the two options compared.
A- Difference in annual energy expenditure in the use phase in MJ between the two options compared.
D- Difference in energy expended in disposal in MJ between the two options compared.
n- Number of years.
i- Social discount rate.

The NPV of the incremental "cash" flow will determine which of the available options leads to a net primary fossil energy use mitigation when compared to a base case. A positive NPEV shows that the extra energy expended in the production of Option II is justified by the energy savings provided by a more efficient use phase. Consequently, Option II promotes fossil energy savings when displacing the reference option (Option I). A negative NPEV leads directly to the opposite conclusion. By comparing all the possibilities among all the technologies-fuel combinations it was possible to rank them according to their efficiency regarding energy savings.

The possibility of different social discount rates was considered in the analysis, differentiating the value of energy use in time. By the evaluation of the behavior of the NPEV for different social discount rates, it was possible to evaluate which of the options leads to more energy savings and which delivers this sooner. The energy savings that are only delivered in the future are strongly devalued when the rate is applied, so by analyzing the NPEV`s behavior in different rates it is possible to determine the "velocity" of the energy saving.

Also, a sensitivity analysis of the NPV of each individual technology option with respect to key parameters (fuel consumption, annual mileage and energy consumption in vehicle manufacture) was performed in order to identify the most important factors and the ones that should be given more attention to achieve the energy savings.

3. Results

3.1 - Primary fossil energy uses

Table 5 shows the data regarding manufacture and maintenance, disposal and consumption of the technologies. Table 6 presents the fossil fuel usage to make available 1 MJ of the fuel/electricity required by the technologies. In Brazil gasoline is only consumed as Gasoline C (Gas.C). In tests procedures that produced the data used in this study, it is a blend of 22% of alcohol and 78% of Gasoline A (pure gasoline) in volume basis.

Table 5: Summary of the vehicle data

		Manufacture and Maintenance	Disposal	Consumption					
		MJ	MJ	km/l/Wh/km			MJ/km		
				Ethanol	Gas. C	Elect.	Ethanol	Gas. C	Elect.
Vehicle	FLEX	90641	2923	8.27	12.00	NA	2.58	2.51	NA
	HEV	95902	2923	14.84	21.45	NA	1.51	1.40	NA
	BEV	112664	2923	NA	NA	184.33	NA	NA	0.66

(GREET, 2015; INMETRO, 2016; JRC, 2013)

Table 6: Primary fossil energy use related to fuels/electricity

	Primary MJ/MJ supplied
Gasoline A (Oil Products)	1.16
Gasoline C	0.98
Hydrated Ethanol	0.08
Anhydrous Ethanol	0.08
Electricity	0.44

(SEABRA et al., 2011) and EcoInvent v.3

To obtain the primary fossil energy use of Gasoline C, it was summed the contribution of the energy provided by the Gasoline A in a fossil primary basis with the contribution from anhydrous ethanol in a fossil primary basis in one liter of Gasoline C. After that, the value obtained was divided by the density. Then it was divided by the low heating value of Gasoline C and the Primary MJ/MJ supplied ratio was obtained.

3.2 - Energy balance and vehicle comparisons

By following the procedure described in the Methodology, the final performance of the Flex vehicle, the HEV and the BEV were obtained. Their life cycle primary energy expenditures are showed in Figure 3:

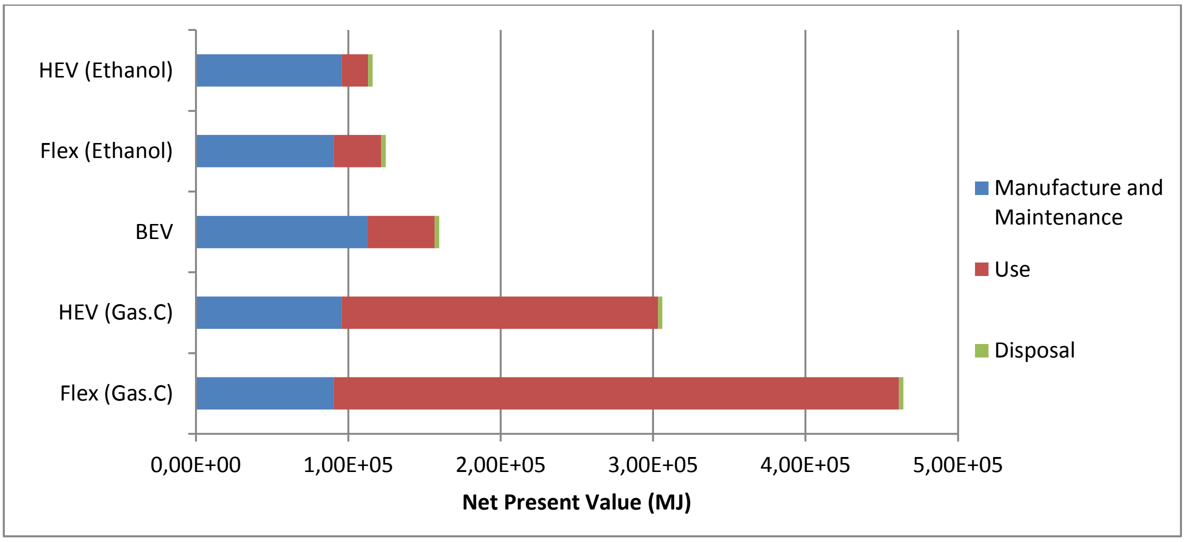

Fig. 3: Energy expenditure along the whole life cycle of the transportation technologies. Gas.C – Gasoline C. The NPV is the sum of all energy consumptions along the life cycle. In this figure the social discount rate is 0%.

As can be seen in Figure 3, technologies that are not using fossil fuels directly presented minor primary fossil energy use during their life cycle. This occurs because the presence of fossil energy in the production chain of ethanol and electricity are much lower than in the liquid fuels` chain. The higher fossil primary energy required for electricity generation in comparison to ethanol production is the reason why BEV has worst results than HEV and FLEX running with ethanol despite its greater energy efficiency in the use phase.

It is interesting to notice the relative shares of energy expenditure shown in Figure 3. In the technologies with the least fossil primary energy intensive NPV the Manufacture and Maintenance is the phase where the majority of the energy is consumed. On the contrary, the most fossil primary energy intensive options have production as a relevant energy expenditure, but the use phase plays the most important role in the energy consumption. In all cases, disposal is practically insignificant in the life cycle energy expenditure.

In order to quantify the benefits of adopting a technology over another, all possible technology-driving power combinations were compared except the ones comparing the same technology with different fuels. Figure 4 shows the NPEV`s of the proposed comparisons.

The options using directly Gasoline C obtained greater NPV`s and the ones using ethanol and electricity smaller NPV`s. Therefore, as can be seen in Figure 4, the substitution of Gasoline C with ethanol or electricity was proved to be highly effective (HEV(Et)-FLEX(Gas.C), BEV-FLEX(Gas.C), BEV-HEV(Gas.C)), due to the different intensities of primary fossil fuel of the production chains of the used energies. In all cases the greater energy investment in the Manufacture and Maintenance phase of the challenger was not determinant for the final result.

Comparisons of different technologies running on the same fuel (HEV-FLEX(Gas.C), HEV-FLEX(Et)) presented a positive NPEV. When running on Gasoline C, the NPEV is considerably positive due to the use phase different efficiencies (higher for the HEV). When running on ethanol the NPEV is almost zero because ethanol`s production chain is little intensive in primary fossil energy, in a way that the higher use phase efficiency of the HEV produces net savings that are enough only to slightly compensate its greater energy investment in year zero.

Comparisons that proposed the substitution of ethanol with electricity or Gasoline C obtained negative NPEV`s (BEV-FLEX(Et), BEV-HEV(Et), HEV(Gas.C)-FLEX(Et)). The electricity production chain is more primary fossil energy intensive than ethanol`s and even though the BEV having the highest use phase efficiency it is not enough to match the HEV and the FLEX running on ethanol. Also, as the substitution of Gasoline C with ethanol produced the highest NPEV, the opposite substitution produced the most negative one due to the same reasons.

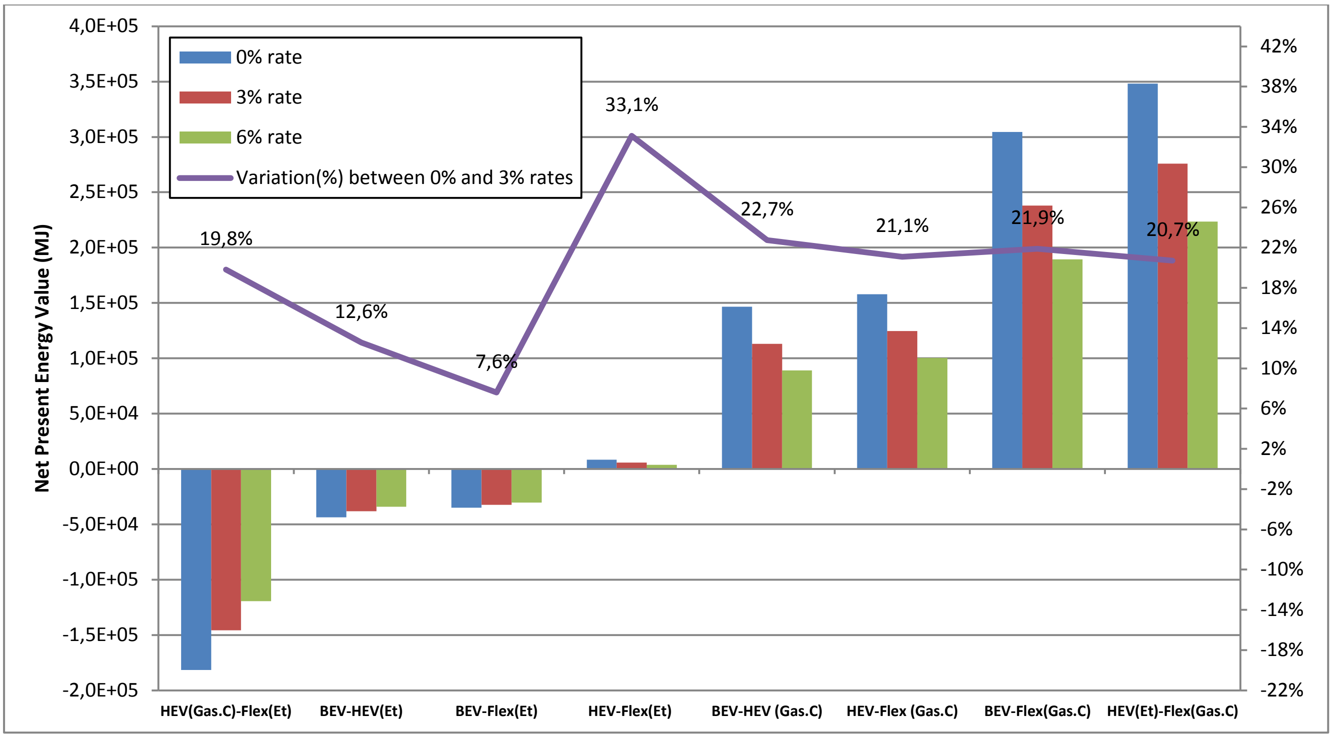

Fig.4: Net Present Energy Value for different technological options and fuels with different social discount rates. In the comparisons, the challenger comes first followed by the reference option (defender). Inside the brackets is specified the fuel used. If only one fuel is specified, it is being used for both vehicles, except in cases the BEV is present because it uses only electricity. HEV-Hybrid Electric Vehicle, BEV-Battery Electric Vehicle.

So, by analyzing Figures 3 and 4, it is possible to rank the options according to the consumption of primary fossil energy: HEV (Ethanol), Flex (Ethanol), BEV, HEV (Gas.C) e Flex (Gas.C).

The social discount rate differentiates the value of energy in time. When positive, it reduces the equivalent present value of a future energy expenditure and practically maintains the value of the expenditures around the present at their nominal value. This means that, if a technology delivers its energy savings far in the future, taking too much time to compensate an extra energy expenditure in the present (vehicle production), its NPEV will be decreased when a positive discount rate is applied. It means that, as the discount rate may be a tool for the society perception of an issue, society undervalues energy savings that would occur in a far future. When applied, it decreases the NPEV (net savings) and consequently shows that if society demands to keep the NPEV as when the rate was zero, the challenger technology must produce a more aggressive saving.

The purple line in Figure 4 shows the variation in the NPEV when the social discount rate is changed from 0% to 3%. The value for each comparison can be directly related to how soon the net energy savings are obtained when compared to the extra energy expended in production.

It can be noticed that comparisons with similar NPEV`s, may have different response in time. For example, the comparisons HEV(Et)-FLEX(Gas.C) and BEV-FLEX(Gas.C) present similar NPEV`s. The first one has a NPEV variation between 0 and 3% of 20.7% and the second one 21.9%. This indicates that replacing the Flex car running on Gasoline C by the HEV running on ethanol has a faster energy saving than when replacing the

Flex car running on Gasoline C by the BEV, even though, globally, both substitutions have similar responses in terms of their NPEV. Additionally, it is interesting to note that HEV-FLEX(Et) comparison has the highest variation among all comparisons. This happens because the difference in the respective use phases is not very high, and to compensate the difference in vehicle production takes more time, resulting in a greater payback time. This analysis is only applicable for the comparisons with positive NPEV, since otherwise there is not even a payback time as the substitution is not worthy in energy terms.

3.3 Sensitivity Analysis

Figure 5 presents a sensitivity analysis of the NPV of the three technologies assessed and their fuel alternatives with respect to fuel economy, annual mileage and the energy expended in vehicle manufacture.

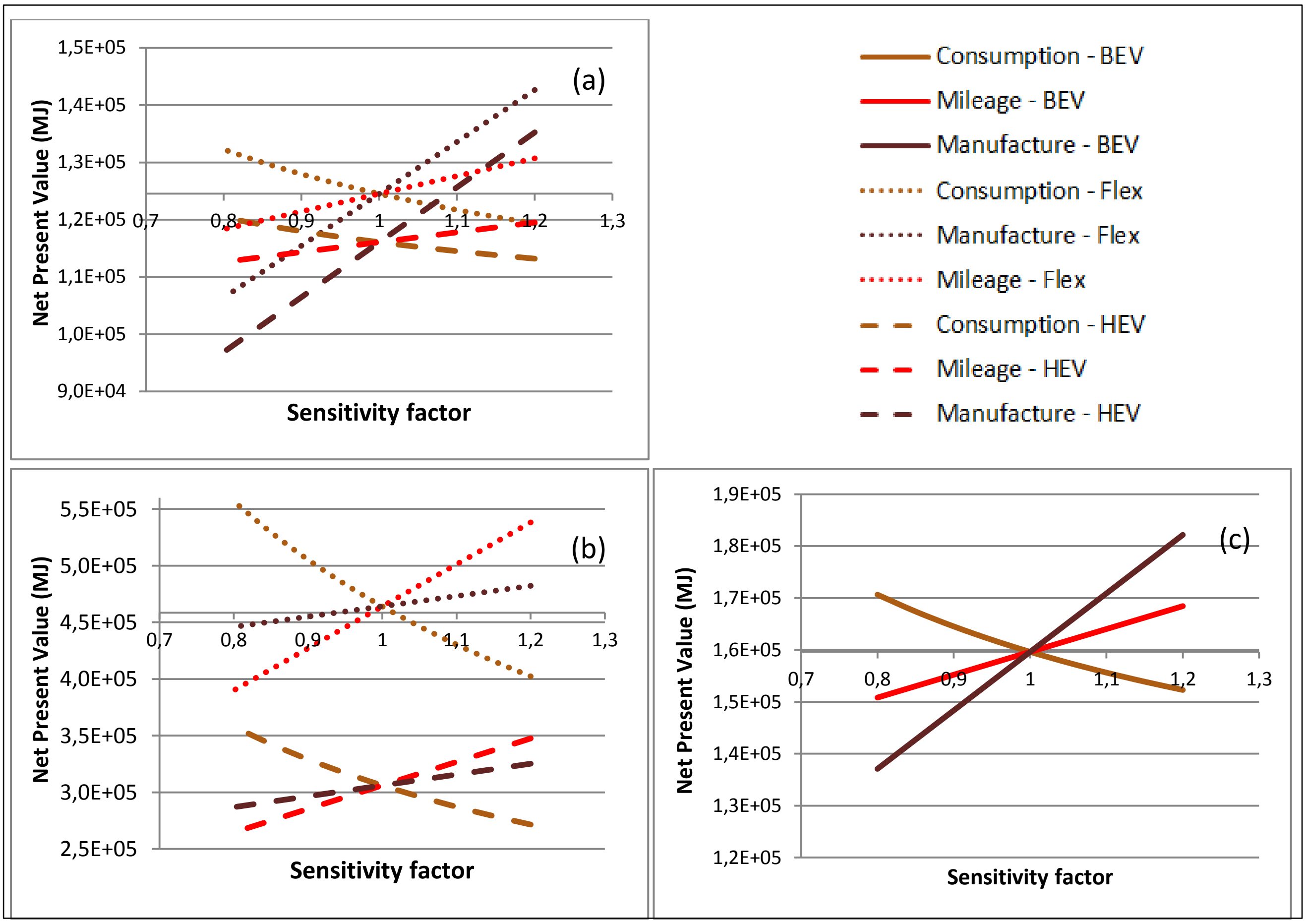

Fig.5: Sensitivity analysis with respect to key parameters. Graph (a) shows Flex vehicle and HEV using ethanol, and Graph (b) when using Gasoline. Graph (c) shows BEV using electricity.

From Figure 5, it can be noted that for FLEX and HEV using ethanol, the greater sensitivity of the NPV is with respect to the energy consumed in the manufacture, because, given the low fossil fuels consumption in the ethanol production chain, factors such as the consumption and the annual mileage become less important. The contribution from the use phase to the life cycle primary energy consumption is greater for the options using gasoline, so annual mileage and fuel consumption are the most relevant parameters, leaving vehicle manufacture as less important. BEV presented a similar behavior of the options using ethanol, since manufacture has a greater share on the NPV. All behaviors are coherent with the shares of each phase in the life cycle primary energy consumption showed in Figure 3.

From this analysis, it can be pointed out that for a given technology (HEV or FLEX) running on different fuels (Gasoline C or Ethanol), the most relevant parameter changes. As concluded above, HEV and FLEX running on ethanol have a lower NPV than when running on Gasoline C. Even though the absolute value of energy that must be invested on their vehicle production is the same, its relative contribution is more important in a life cycle with a lower NPV (running on ethanol).

4. Conclusion

Among the main technologies that have been considered to reduce the primary fossil fuel consumption in the transport sector, the HEV using ethanol was the best option under the conditions assumed in this study. Obviously, technologies that use directly a fossil fuel had the worst results. For the three least fossil fuel intensive options (FLEX:Ethanol; HEV:Ethanol and BEV), it must be pointed out that, in order to improve even further their net energy savings, an investment aimed at the reduction of the energy consumption in the vehicle manufacture is recommended, while for BEV, the R&D focus should be on increasing the battery lifetime and developing second life applications for it. For the options using directly fossil fuels, the focus should be on increasing their use phase efficiency, since it is where most of the energy consumption occurs.

Although both HEV and FLEX running with ethanol proved themselves as the best options for the reduction of primary fossil fuel consumption in private transportation, it must be pointed out that it is impossible in the present, and very unlikely in the future, all Brazilian fleet to be able to run solely on ethanol. In fact, hydrated ethanol is not even a reality for all Brazilian states in the present, as there are locations where its price almost never justifies the substitution of gasoline.

It can be inferred from this work that the addition of anhydrous ethanol to Gasoline A already plays an important role in reducing the primary energy demand. As results showed, oil products require 16% of the energy they carry to be available, while Gasoline C provides more final energy than fossil energy it requires for production. So, if Gasoline A were commercially adopted in Brazil, the use of gasoline would be even more intensive in primary fossil energy.

BEV is also an interesting choice among the options, although not as good as HEV and FLEX running with ethanol. In this study its performance was evaluated using the average primary fossil energy consumption of Brazilian electricity mix, but it must be pondered that the introduction of the BEV in the Brazilian fleet may create a demand that is able to change considerably the electricity generation profile, possibly with more intensive use of thermoelectric facilities. Naturally, the electricity generation capacity could also be expanded with a greater penetration of renewable sources such as wind, hydro, photovoltaic, among others.

This study evaluated the life cycle energy performance of three technological options regardless of the problems that may come with their adoption. The issues raised above, such as the expansion of the ethanol production or the evolution of Brazilian generation mix, were beyond the proposed scope. Of course, to provide a more complete answer to policymakers on which path to go requires further research. But, primarily, the results point to the use of a diversified fleet, eliminating the worst options. The use of biofuels, the Hybrid technology and the pure electric vehicle technology are not necessarily competing; actually it is most likely that they will be adopted complementarily in order to not overload a sector of the economy, such as biofuels or electricity sector, and to obtain the perceived energy savings when replacing options using directly fossil fuels.

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