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energies

Article

Energy, Exergy, and Emissions Analyses of Internal Combustion Engines and Battery Electric Vehicles for the Brazilian Energy Mix

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Abstract: Exergy is a thermodynamic concept that ponders the quality of energy. It evaluates the irreversibilities of a machine, demonstrating its capacity to perform work associated with energy conversion. This article focuses on directing public policies and vehicle development toward their most proper usage worldwide. In the urban mobility scenario, there is an obvious demand to decrease greenhouse gas (GHG) emissions. In addition, the internal combustion engine (ICE) experiences considerable energy losses through heat exchange through the radiator and exhaust flow gases, which are not considerable in battery electric vehicles (BEVs) since there are no exhaust gases subsequent to combustion, nor combustion itself. This work presents longitudinal dynamics simulations of passenger vehicles to understand the magnitude of exergy destruction in ICEVs and BEVs, considering the Brazilian and European Union electric energy mix. Overall, the method can be applied to any other country. The simulation and model parameters were configured to match production road vehicles commercialized in the Brazilian market based on different versions of the same model. Two vehicle dynamic duty cycles were used, one relating to urban usage and another to highway usage, resulting in an overall exergy efficiency of around 50–51% for BEVs considering the exergy destruction in power plants. In contrast, ICE has an average efficiency of 20% in the urban cycle and around 30% in the highway cycle. By comparing the overall equivalent CO_2 emissions, it is possible to conclude that EVs in the European energy matrix produce more GHG than ICE vehicles running on ethanol in Brazil. Nevertheless, there are increasing uses of coal, natural gas, and oil thermal electric power plants, raising the question of how the transition may occur with a general increase in electrification since there is an increasing electric expenditure in all sectors of society, and the renewable energy plants may not meet all of the demand.

Keywords: exergy; internal combustion engine; battery electric vehicle; efficiency

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1. Introduction

The concept of exergy is scientifically proven and has been accepted for the comparison of work performance capability in different machines based on a theoretical machine, given the potential of some property (a gradient) [1]. For internal combustion engine (ICE) vehicles, the fuel chemical exergy is the maximum work potential [2].

In the automotive context, exergy can supply insights into the comparison of the amount of destroyed exergy between different concepts applied to several components, such as the internal combustion engine, the electric engine, peripheral systems, and many other losses. This makes it possible to understand which concept can use energy better for automotive applications by reducing irreversibilities in the energy conversion process. The exergy analysis can also provide insights into the technological increments for each concept, as seen in [3,4].

Florez-Orrego et al. [5] calculate the exergy costs for electricity by exergy comparison by integrating the entire amount of work performed by a vehicle in the ABNT NBR 6601 cycle, equivalent to FTP75, and conclude that ICE vehicles have from around 5% to 10% overall exergy efficiency, whereas BEVs perform with an exergy efficiency up to 34%.

The recharging energy of BEVs relies on the electric energy available in the local grid, using the original source as the root of the power produced. Infrastructure is rarely available to recharge EVs using solar panels [6]. Hence, there is an incentive for BEV owners to use moments where renewable energy is available with a so-called "white tariff" to recharge their vehicles [7,8], financially charging for energy use based on the hour of consumption. The emissions and overall energy and exergy efficiency obtained from an electric vehicle directly depend on the means of energy conversion in the recharging environment, as reviewed by [9]. Another interesting comparison is the driver's behavior, as demonstrated by [10], where the authors surveyed intelligent driving vehicle trajectories. There may be an increase in energy savings, where the authors aim to give a guideline to future researchers in the field.

In Brazil, most of the electricity originates from hydroelectric power plants, which positively contribute to greenhouse emissions from electric power conversion, along with wind and solar generation [11]. Nevertheless, there is an increasing number of thermal electric power plant (coal, natural gas, and oil) sources due to dry periods or peak demand, avoiding undersupply. This resource is usually considered in the southwest, where the larger urban centers and populations are located [6]. This is also associated with the expectation of an increase in thermoelectric and other nonrenewable power sources for electricity generation, as mentioned by Fernandéz et al. [12]. Doucette and McCulloch [13] also mention that countries with high demand and infrastructure based on thermoelectric plants with non-renewable fuels shall have a significant increase in CO_2 along with electric vehicle demand.

A comparison of the electric matrix with the energy mix shows the fragility of this sector, mostly related to transportation services, usually in large trucks with intensive CO_2 emissions. Hence, a complete understanding of passenger (or commercial) and truck vehicles' behavior is crucial to address the Sustainable Development Goals (SDG) 11, 12, and 13. In this work, the scope relies on the analysis performed for passenger vehicles. Several authors show the most significant problems related to $CO_{2,eq}$ emissions in electric vehicles (BEV) are related to battery production. As mentioned in Ref. [14], the raw materials used to produce a battery contribute to 50% of the emissions in the lifespan of the car (for more than 100,000 km driven). These are related to rare metals used in these energy storage systems. This is a reason why there is no consideration for the production or disposal of batteries in the present study, since the proposal is to show compassion disregarding this component (giving the best-case scenario to the EV and worst-case scenario to the ICEV).

Vehicle power sources in Brazil are characterized by fuel blends as defined by INMETRO [15] and ANP (Brazilian National Agency for Petroleum, Natural Gas and Biofuels), where the gasoline available for light vehicles is blended with ethanol (E22, up to 27% anhydrous ethanol by volume, or close to 24% by mass), which is also available in its pure form, mixed with a small percentage of water (E100, hydrous ethanol) [16]. The anhydrous ethanol content in E22 gasoline can vary from 18% to 27.5% by volume [17]. It is important to highlight that differently from the electric mix, the energy mix has a high percentage of non-renewable energy sources [6]. Moreover, the consideration to INMETRO is widely used in Brazil, supported by the National Electrical Energy Conservation Program and Energy Efficiency Labeling as discussed by Mady et al. [18].

Ethanol is an optimistic approach to reducing overall emissions for passenger light vehicles, as explained by Goldemberg [19], since there are no fossil fuel emissions from tank to wheel. However, it is known that overall total emissions from E100 ethanol are not fully compensated for in the sugarcane cycle, resulting in 23 g $CO_{2,eq}$/MJ worth of greenhouse gas net emissions, including usage, processing, transport, cultivation, and others for first-generation ethanol (based on sugarcane) [20].

It is very important to distinguish the scope of the fuels used for stationary thermal power plants and the automotive transport sector in Brazil. Brazilian's national energy balance [21] shows thermal power plants' fuel sources as biomass, coal, and oil products, while fuels regularized by the national petroleum agency [16] include gasoline, ethanol, and biodiesel, which make a lower contribution to greenhouse gases compared to stationary power plants, even though the overall efficiency varies greatly in automotive use (from 11% to 27% for gasoline engines [22]), while thermal power plants tend to have higher efficiency (up to 49% for conventional thermal electric power generation in Europe [23]). The European Union also has a privileged energy mix (almost 20% of the renewable share) based on increasing wind and solar energy, making its region the one with the highest rate of decreasing $CO_{2,eq}$ [24]. However, geopolitical concerns are currently delaying these programs.

Given the motivation shown, the objectives of this work are to calculate and compare exergy efficiency for different powertrain configurations while also comparing overall emissions, on a well-to-wheel basis. In that sense, it is possible to draw accurate comparisons of destroyed exergy and well-to-wheel emissions for the studied powertrain configurations in both cycles. The presented methodology is coordinated with advances presented in different papers [5], standardizing the data and enabling the analysis of vehicles on the same basis. These figures can enable policymakers to decide on product development and public policies based on better directing resources and energy to their best uses. The uniqueness of the Brazilian scenario relates to the production of fuel with a low carbon footprint, with over fuel 40,000 stations in the country [25]; hence, the infrastructure is ready. Since the significant production (crops and bio-refinery) sites are in the Southeast region, no carbon is associated with deforestation nor with competition for food production. A country with similar perspectives is India, although they do not yet have the same historicity as Brazil in the area [26].

2. Materials and Methods

In this section, the thermodynamics of the ICEV and BEV will be explored in detail, where Figure 1 shows a simplified version of the path of different fuels to the vehicle "tank" as well as the possible energy and exergy losses for both types (ICEV and BEV). In the final part of the representation, there are indications of enthalpy losses to the environment from exhaustion flue gases (ICEV), exergy transfer to the environment associated with heat, and other exergy losses associated with friction, fuel, the batteries, and the tank. The energy and exergy analyses of these processes are based on previous studies by Fusco and Mady [27].

2.1. Vehicle Dynamics

The determination of the energy usage in a vehicle occurs by its longitudinal dynamics, which take into account the driving force and all resistance forces (air, rolling, slope, and others), as reviewed by [5,28]. The overall forces found in an automobile can be seen in Figure 2 and are defined through Newton's second law, Equation (1), resulting in Equation (2). This section is a logical continuance of the outcomes presented by [29,30].

$$\Sigma F_{ext} = ma = m\frac{dV}{dt} \tag{1}$$

In Equation (1), ΣF_{Ext} stands for the resultant of all external forces [N] during acceleration, m for the mass [kg], and $a = dV/dt$ for the acceleration in [m/s^2], which is the variation in the velocity over time. During deceleration, traction force is considered null, and braking force takes place in the opposite direction. Braking force can occur by activating the actual brake system (where kinetic energy is turned to heat) or by regenerating electric energy (in the case of BEVs).

$$F_{Traction} - F_{Rolling} - F_{Drag} - mg \sin\theta = m\frac{dV}{dt} \quad (2)$$

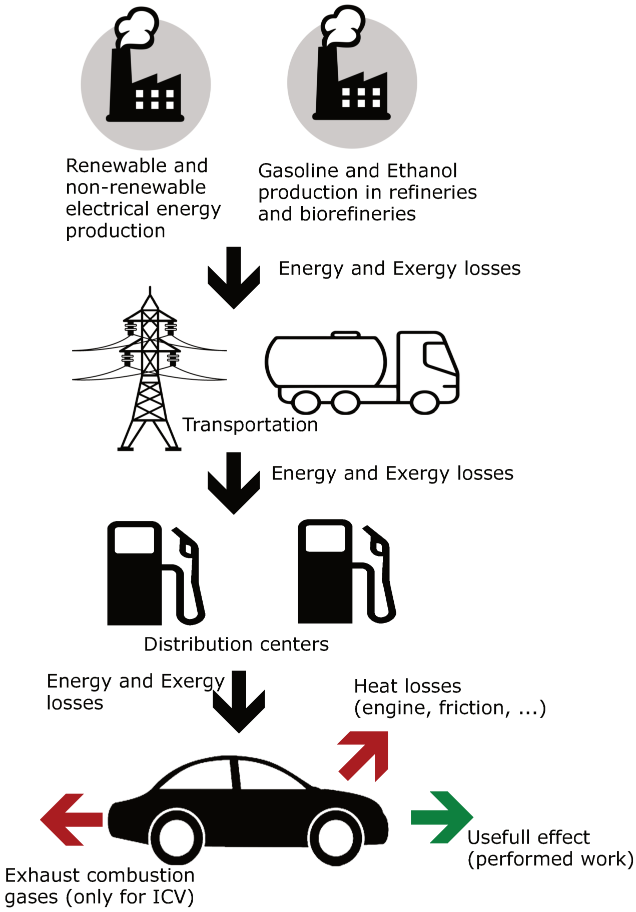

Figure 1. Simplified representation of the inputs and outputs of vehicles' and the fuel path to become movement.

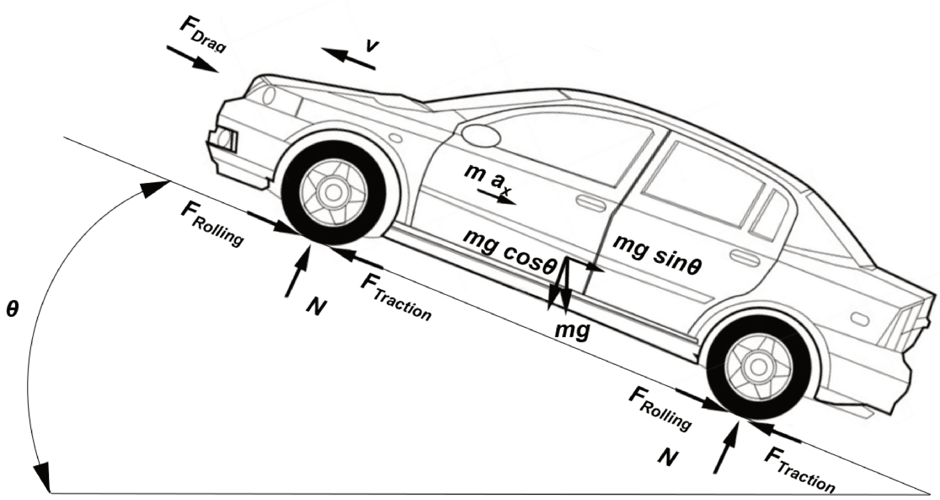

Figure 2. Free body diagram of a moving vehicle during acceleration, obtained in Ref. [5], adapted from [28].

In Equation (2) [31], $F_{Traction}$ is the traction force from the powertrain on the tires to prevent sliding, $F_{Rolling}$ is the rolling resistance exerted by the ground on the tires against the movement of the vehicle, and F_{Drag} is the drag force, with no relative wind velocity and a constant drag coefficient. The $mg \times \sin\theta$ relates to the longitudinal share of vehicle weight, which directly opposes traction force whenever the vehicle is on an inclined plane. This is not the case for standard vehicle duty cycles, such as the ones approached in this work, due to the sole representation of flat areas.

2.2. Thermodynamics

By comparing the energy source and its quality, it is possible to determine the amount of destroyed exergy in an energy conversion process, in this case, in a standard test cycle such as the ones shown in Figure 3.

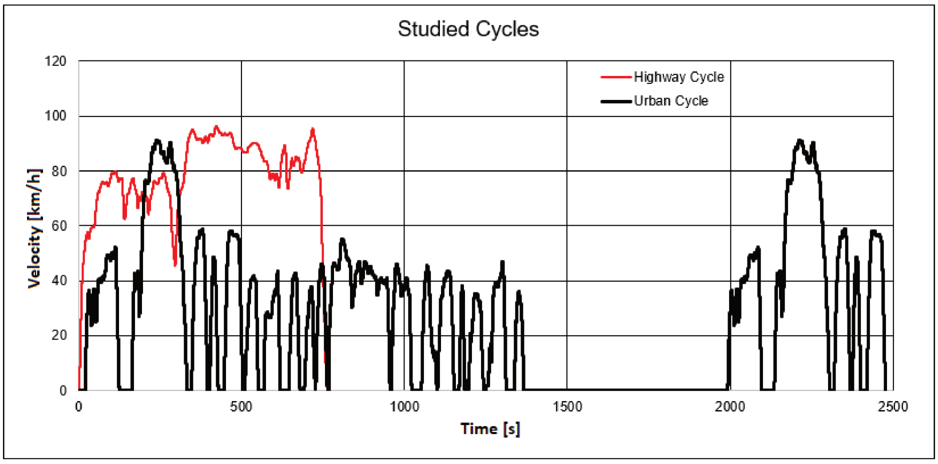

Figure 3. Definition of urban and highway cycles based on ABNT NBR 7024. Figure obtained by the authors.

Equation (3) is used to assess a flow rate's physical exergy: $\dot{B}_{Ph} = \dot{m}b_{Ph}$, representing the fuel consumed, flue gases, which are examples of these exergies. Where for a given difference in the temperature (T) and the pressure (P) (or another intensive independent property) of a substance concerning its state at the reference environment T_0 and P_0, it is possible to calculate the enthalpy and entropy ($h(T,P)$ and $s(T,P)$) at the actual state and for the reference one $h_0(T_0,P_0)$ and $s_0(T_0,P_0)$:

$$b_{Ph} = h - h_0 - T_0(s - s_0) \quad (3)$$

At the same time, when there exists a difference in a substance's chemical potential (μ) and its components' chemical potential (μ_0) under environmental conditions, there is potential to perform some theoretical work, referred to as chemical exergy. Equation (4) shows a definition to evaluate the chemical exergy based on its lower heating value and the values of ϕ defined by [32].

$$\phi = \frac{\dot{m}_{fuel} b_{Ch,fuel}}{\dot{m}_{fuel} LHV} = \frac{b_{Ch,fuel}}{LHV} \quad (4)$$

The overall exergy of a specific fluid can be determined by the sum of all its exergies, as shown in Equation (5), including b_{Ke} and b_{Pe}, the kinetic and potential exergies. Hence, it becomes possible to discriminate between different power sources through Equation (6) on the same thermodynamic basis. This defines the overall balance relating to the exergy properties of a determined source (temporal variation of the exergy, $\mathbf{B}_{CV}$, in the control volume) $\frac{d\mathbf{B}_{CV}}{dt}$, the amount of exchanged heat $\dot{Q}_{CV}$, the amount of performed work $\dot{W}_{net}$, and the destroyed exergy $\dot{B}_{des}$, also balanced with the exergy carried by any bodies or fluids entering or leaving the system, represented by entering and leaving masses $\dot{m}_{in}$ and $\dot{m}_{out}$ and their respective specific exergies b_{in} and b_{out}. As previously mentioned, this work aims to compare the destroyed exergy in vehicles that uses different powertrain configurations, including those using electricity as a power source, which carries exergy from electric energy generation [32].

$$b = b_{Ph} + b_{Ch} + b_{Ke} + b_{Pe} \tag{5}$$

$$\frac{d\mathbf{B}_{CV}}{dt} = \dot{m}_{in} b_{in} - \dot{m}_{out} b_{out} + \dot{Q}_{CV}\left(1 - \frac{T_0}{T}\right) - \dot{W}_{net} - \dot{B}_{des} \tag{6}$$

The traction force work is calculated by gathering traction force and integrating it as a function of distance between two interval points. Then, lost work (destroyed exergy) can be calculated by fuel exergy (chemical exergy), exhaust gas exergy (thermal exergy), and exergy related to heat exchanged between the engine and the vehicle's surroundings [27]. Unlike the authors, our system's frontier is considered the environment. Therefore, this means that all exergy lost by the vehicle is destroyed in the environment and accounted for in the car countability of destroyed exergy. Hence, for steady-state conditions, Equation (6) becomes $\dot{B}_d = \dot{B}_{consumed} - \dot{B}_{usefull}$. The exergy losses associated with heat transfer are considered at a boundary at T_0, making them internal irreversibilities instead of accounting for them as destroyed exergy in the environment.

The overall exergy efficiency is given by Equation (7), which connects the total amount of work performed and the exergy consumed from the power source [5], while energy efficiency is shown in Equation (8), where LHV_{fuel} stands for the fuel's lower heating value, and $\dot{E}$ stands for the amount of energy consumed in the interval. The terms $\dot{B}_{consumed}$,$\dot{E}_{consumed}$ represent the energy and the exergy input in the system or consumed by the process to generate some useful effect (movement of the car).

$$\eta_B = \frac{\int_1^2 F_t dx}{\dot{m}_{fuel} b_{fuel}} = \frac{\int_1^2 F_t dx}{\dot{B}_{consumed}} \tag{7}$$

$$\eta_{En} = \frac{\int_1^2 F_t dx}{\dot{m}_{fuel} LHV_{fuel}} = \frac{\int_1^2 F_t dx}{\dot{E}_{consumed}} \tag{8}$$

2.3. Vehicle Duty Cycles

Two duty cycles were studied, while the fuel and overall energy-specific consumption were obtained according to a mix of both cycles, as determined by ABNT NBR 7024, in order to compare the average fuel and energy consumption for all studied configurations with reference values from INMETRO [15]. The FTP75 (or urban) cycle, shown in Figure 3 in black, is used in order to study vehicle behavior in a simulated city environment, where the average speed is rather low, and there are many stops. It is defined by the EPA (United States Environmental Protection Agency) as a Federal Test Procedure (FTP) containing a cold start phase, a cold start stabilization phase, and a hot start phase, considered to be a "city driving" cycle to measure the tailpipe emissions and fuel consumption of passenger cars [33]. The highway cycle, also shown in Figure 3 in red, is used to understand vehicle behavior in intercity/highway environments, where the average speed is high, and there are no stops. Average fuel consumption can then be calculated as a weighted average between both cycles, using 55% for the highway and 45% for the urban [34] cycle, as shown by Equation (9).

2.4. Simulation Conditions

The simulations are performed in the commercial software AVL Cruise, Version R2023.1 © to obtain data on the energy consumption of the internal combustion engine (ICEV) and electric vehicles (BEVs) in fixed-usage cycles (FTP75/Highway). From the dynamics needs imposed throughout the cycle, which sets speed targets as a function of distance, it is possible to obtain the energy demand while also considering energy losses from the exhaust flow gases, engine heat to the environment, and other sources of energy consumption. These last losses are the secondary consumers, electronic control units, mechanical devices, and others, resulting in a mature evaluation of vehicle energy consumption. The vehicle used for all configurations has the properties shown in Table 1, which is based on the Volvo XC40 platform for the ICEV and BEVs, the vehicles among the highest-selling BEVs in the Brazilian market [30]. Furthermore, the engine properties and the full load curve are inputted into AVL Cruise software, along with engine-specific power consumption. For all vehicles considered, the axle distance is set as 2702 mm, the front area is set as 2.62 m^2, and the drag coefficient is set as 0.34 [35,36]. Power and torque curves are modeled according to the data shown in Table 1 and standard models for combustion and electric engines. The idea of this article is a proof of concept, hence to show the advantages and disadvantages of the same model, with BEV and ICEV. The fuel consumption map is based on a standard internal combustion engine found in the AVL Cruise database, adjusted for a 2000 cm^3 displacement engine. Even though the peak powers are different, as the results show, the demands imposed by the vehicle duty cycles used in this study demand power over 70 kW (or 94 hp); therefore, vehicles can be compared without technical limitations.

Table 1. Vehicle year of fabrication, mass, peak power, peak torque, and urban consumption.

Parameter	ICEV (E22)	BEV
Year	2021	2022
Mass [kg]	1684	2184
Peak Power [hp]	190 at 4700 rpm	408 at 4350–13,900 rpm
Peak Torque [Nm]	300 at 1380–4020 rpm	660 at 0–4380 rpm
Urban Consumption	9.5 km/L	25 kWh/100 km
Axle Distance [mm]	2702	2702
Front Area [m^2]	2.62	2.62
Drag Coefficient	0.34	0.34

AVL Cruise is a software often used to compare different vehicle configurations or entire vehicles, used in both industry and academic fields. It is based on the longitudinal dynamics Equations (1) and (2), among others, and calculates multiple vehicle parameters when performing a determined cycle or task. Moreover, it considers gear changes and force behavior and calculates realistic results (validated over different aspects through the literature) that can be used in multiple development methods, such as hardware-in-the-loop and software-in-the-loop, as well as tested models [37]. Analyzing energy usage and waste, after-treatment system temperature, and exhaust gases is possible. For these reasons, it was the method of choice for calculating vehicle energy usage in this article.

No energy recovery systems are considered for the ICEV. Since the vehicle duty cycles studied refer to completely plain surfaces, no regeneration from downhill driving is considered. Specifically for electric vehicles, energy regeneration is considered during the deceleration/braking situations imposed by the mentioned cycles. This routine is considered in the simulation software and can be better seen in the Results section.

Other energy losses not mapped by the dynamic model were distributed in the energy consumption map of the electric machine for the electric vehicle. In this way, it was possible to adjust the energy loss model by using INMETRO's energy efficiency labeling program [15] as a reference, in order to generate results that were comparable to reality. Accordingly, it is understandable that the model was then calibrated according to the energy losses seen in the results of physical tests, meaning that the model correlated with reality. Vehicle mass is used as a parameter for the simulations.

For the ICEV, a mix of gasoline and anhydrous ethanol is considered the standard fuel in Brazil, as detailed in Ministry of Agriculture, Livestock and Food Supply (MAPA)—No. 75 from 2015, [38]. According to [27], the E22 fuel blend, commercially available in Brazil, has a lower heating value of 39.26 MJ/kg and a density of 715 kg/m^3. In parallel, a mix of E100 hydrous ethanol is also considered (since Brazil has been a leader in the technology and usage of ethanol for the past 30 years, as seen in Ref. [39]), with 24.80 MJ/kg as the lower heating value and a density of 789 kg/m^3. Specific exergy values for both fuels are calculated based on Ref. [27,32] and are shown in Table 2.

Table 2. Fuel conditions for E22 and E100 [27,32].

Fuel	ρ [kg/m^3]	*LHV* [MJ/kg]	ϕ [-]	*b* [MJ/kg]
E22	715	39.26	1.0741	42.17
E100	789	24.80	1.1226	27.84

2.5. Electric Mix Definition for Exergy Calculation

The exergy efficiency comparison method is carried out according to Equation (7), where the fuel or source exergy is compared solely to work performed by an engine, motor, or complete vehicle. Other exergy comparison methods are used, such as the Sankey diagram, with absolute and percentual values.

The energy mix of electric vehicles is analyzed to assess the electric power generation and its destroyed exergy over the well-to-wheel analyses, contemplating the full energy conversion process from the electrical power generation source to the work performed in the vehicle itself. For the Brazilian mix, the BNE [21] was taken for the year 2021, as also listed in Table 3. For comparison purposes, the European average electric matrix for 2020 is also shown in Table 3 [40], excluding geothermal electric energy generation, which was worth 0.57% of all of the electric energy generated in Europe in 2020. Solar energy considers the thermal cycle shown in Ref. [41], not considering photovoltaic electricity production. It is important to highlight that the method applied in this work is also valid to any other electric power generation mix, as long as the data on the percentage of each power generation source are available.

Table 3. Brazilian [21] and European Union [40] electric power generation.

Power Source	Brazil [%]	European Union [%]
Hydroelectric	63.4	17.28
Natural Gas	11.5	21.36
Wind	12.6	12.9
Biomass	8.4	5.99
Coal and Derivatives	2.8	15.17
Nuclear	2.5	20.98
Petrol and Derivatives	2.2	1.32
Solar	1.3	4.0

The original exergy dispensed from the energy source is then calculated according to Table 4; every electric power source from the Brazilian mix carries a different energy efficiency ratio and exergy content, which then leads to the calculation of the overall exergy efficiency for the consumption of electricity provided by this mix [5]. This also takes into consideration the efficiency of electric transmission in Brazil, which is taken as 84% [42], specifically for hydroelectric power generation, meaning 16% of the energy is lost in transmission due to the distance between hydroelectric stations and major urban centers. The exergy and energy efficiencies for electricity production are then carried out towards the automotive scope via well-to-wheel analysis. The overall exergy efficiency considered for the electric mix is a weighted average of the exergy efficiencies for each electric energy production method according to the percentage considered for each electric mix.

Table 4. Exergy calculation for electric energy production based on Refs. [5,41,43–47].

Source	η_{En} [%]	LHV [MJ/kg]	ϕ [-]
Hydroelectric	82%	-	1
Natural Gas	34.3%	47.33	1.0586
Wind	45%	-	1
Biomass	42.84%	4.44	1.1622
Coal and Derivatives	35%	25.44	1.0958
Nuclear	32%	4193617	0.95
Petrol and Derivatives	40%	41.99	1.0655
Solar	15%	-	0.9375

The overall efficiency is then calculated based on the amount of work performed by the electric machine and the amount of energy input or gained. It can also be associated with the electricity generation matrix, as shown in Table 3, in order to calculate the well-to-wheel energy or exergy efficiency for different electric matrixes.

Vehicle-specific autonomy is defined as the kilometers run with one liter of fuel (or comparable energy measure) for comparison with reference values for energy consumption. Therefore, according to INMETRO and ABNT NBR 7024, the average vehicle autonomy can be calculated using Equation (9), according to the autonomies obtained using urban and highway cycles.

$$A_{avg} = \frac{1}{\frac{0.55}{A_{urb}} + \frac{0.45}{A_{hgw}}} \tag{9}$$

Equivalent CO_2 emissions per MJ of consumed electric energy, including the production, processing, and transport of fuels can be calculated for both Brazil's energy matrix [48], E22 fuel [49], and E100 fuel [28], according to the emission rates shown in Table 5. Europe's average equivalent CO_2 is shown according to data from the European Environment Agency [50]. The high equivalent CO_2 content considered for the European electricity matrix can be traced to the high dependency on coal, natural gas, and oil for electric power generation, as seen in Table 3.

Table 5. CO_2 equivalent emissions [20,48–50].

Energy Source	CO_2 Emission	Green Matrix
Electricity	25 g CO_2/MJ	Brazil
Electricity	85 g CO_2/MJ	Europe
E22 Fuel	77.5 g CO_2/MJ	Brazil
E100 Fuel	23 g CO_2/MJ	Brazil

3. Results and Discussion

3.1. Results for FTP75 and Highway Cycles for the Brazilian Electric Mix

By simulating the conditions shown in Figure 3 and the vehicle properties shown in Table 1, it is possible to obtain the results shown in Table 6 for the urban vehicle duty cycle. This shows the results for the FTP75 cycle with E22 and E100 fuel for the ICEV, as well as for BEVs. First, on the tank-to-wheel and well-to-wheel basis, electrical engines are always more efficient and have lower values of input and destroyed exergy. Moreover, there are no tailpipe and directly associated GHG emissions in the urban center that are directly associated with this specific duty cycle. The ICEV always has a higher exergy loss to the environment from the exhaust gas flow with high physical exergy and pollutants. Considering a more holistic overview, internal combustion engine vehicles use a level of exergy twice as great as an electric vehicle charged in Brazil, considering the whole electric mix on a well-to-wheel basis. This fact must be considered in future energy policies to improve health in urban centers, avoiding intoxication with high exposure to combustion residues [51], for instance, in avenues. In this table, η_b considers the tank-to-wheel efficiency for ICEVs, while considering the well-to-wheel efficiency for BEVs (including the exergy efficiency for the electric mix and electric power distribution). The same applies to other tables in this paper.

From the data shown in Table 6, it is possible to understand that both the exergy efficiency and destroyed exergy benefit from the electric powertrain, which relates to energy recovery systems in the electric vehicle, more specifically from braking regeneration. It is necessary to bear in mind that energy consumption/regeneration varies greatly for an electric vehicle in the FTP75 cycle (due to simulated traffic, as shown in Figure 3). From the same table, it is also possible to understand that E22 and E100 ICEV perform the same amount of work since the same vehicle model is considered (regarding weight, aerodynamic, and tire losses), while the BEV performs additional work due to the acceleration of a heavier mass (considering information from Table 1. Figure 4 shows the power and accumulated energy consumption for both ICEVs and BEVs. The negative values refer to the engine brake, which does not assist in reducing consumed energy in the ICEV (only by avoiding the idle state in the engine through fuel cut-off, which ultimately saves fuel). It is possible to observe that the amount of energy used for the ICEV is much higher when compared to the BEV. This is a consequence of the average higher power used in the ICEV, whereas the BEV has an overall lower power usage (shown in yellow dots), and the ICEV has higher power peaks. It is essential to highlight that this study compares existing models sold in the Brazilian market as an example since there are references for both powertrain conditions. Note that the energy recovery due to the available battery in BEVs lowers its energy consumption and avoids irreversibilities in the driving cycle.

Table 6. Results for the FTP75 cycle. The first column indicates the type of fuel, followed by the exergy efficiency of the engine (η_b), the performed power ($W = \int_1^2 F_t dx$), the exergy efficiency of the vehicle (η_b), and the exergy consumed from well-to-wheel ($B_{consumed}$).

Source	η_b (Engine)	W (Performed Power)	η_b	$B_{consumed}$ (WtW)
E22	20.9%	9.8 MJ	19.5%	49.9 MJ
E100	21.8%	9.8 MJ	19.4%	50.1 MJ
Electricity	97.8%	11.6 MJ	50.3%	25.0 MJ

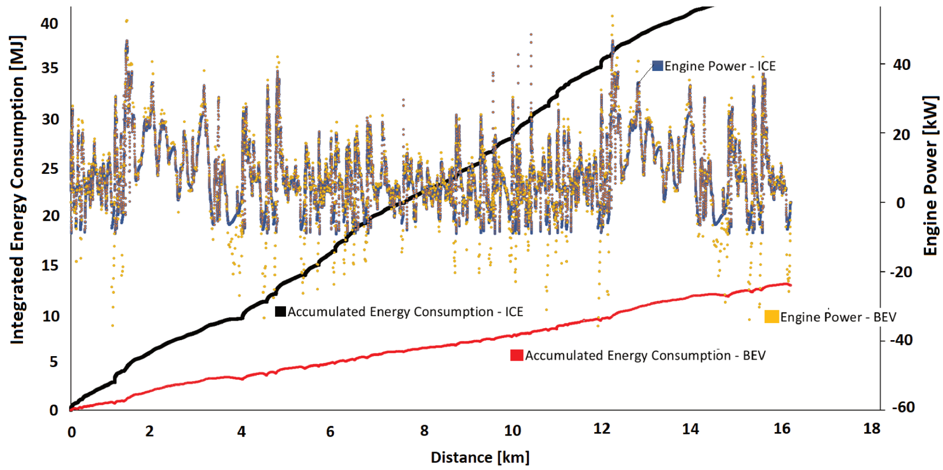

Figure 4. Integrated energy consumption for ICEV and BEV during the urban cycle.

For the highway cycle, it is possible to detect through Table 7 an increase in energy efficiency from the electric vehicle. Nevertheless, for the ICEVs, there is also a significant increase in the exergy efficiency (in this case, proximate to 30%). Therefore, it is possible to conclude that even though BEVs are more efficient, using the ICEV in highway cycles and BEVs in urban cycles might be a reasonable direction of research toward lowering pollutants in cities and avoiding a higher consumption of electric energy. This point opens avenues for future works, such as cold-phase emissions and efficiencies for the ICEV. Moreover, a specific analysis of taxis and app drivers that use vehicles in situations of higher efficiency would be a direction for future analysis. Herein, some pieces of information call for policymakers to create additional incentives for the Brazilian scenario; there is a need to understand the final use and operational factors of the vehicle, such as distance, traffic condition, weight, and usage, among others, as shown by [27,29,30].

Table 7. Results for the highway cycle.

Source	η_{en} (Engine)	W	TtW $-\ \eta_b$	$B_{consumed,WtW}$
E22	26.2%	8.8 MJ	24.4%	32.5 MJ
E100	30.2%	8.8 MJ	29.28%	33.9 MJ
Electricity	98.49%	9.1 MJ	50.7%	25.2 MJ

From both Tables 6 and 7, it is possible to find a quite high discrepancy between E22 and E100 energy efficiencies. This can be explained by a number of authors, such as the results found by [27]. A few of the factors involving higher energy efficiency for ethanol include a higher fuel mass flow (since it has lower LHV when compared to gasoline, or E22), which lowers the temperature in the combustion chamber (also related to higher vaporization heat for ethanol) and, therefore, requires less cooling effort from the engine. The lower temperature in the combustion chamber also results in a reduction in compression power losses. On the other hand, since E100 has a higher exergy content when compared to E22, as seen in Table 2, it is possible to see a reduction in the exergy efficiency when compared to the energy efficiency for ethanol.

Similar to Figure 4, it is possible to use Figure 5 to see a comparison of the energy consumption and demand in the highway cycle. It is possible to see less recovery from the BEV brake-regeneration system, as well as leaner consumption curves resulting from no stops during the cycle (differently from the urban cycle, where stops simulate traffic). As expected, the BEV power points are more dispersed, both positive (consumption) and negative (regeneration), whereas the consumption points follow a similar pattern to the ICEV power consumption points. Additionally, similarly to Figure 4, the ICEV consumes more energy than the BEV but proportionally less than in the urban cycle. The engine power for the ICEV is averagely higher as well, while the BEV shows less brake regeneration (in negative values), as previously mentioned.

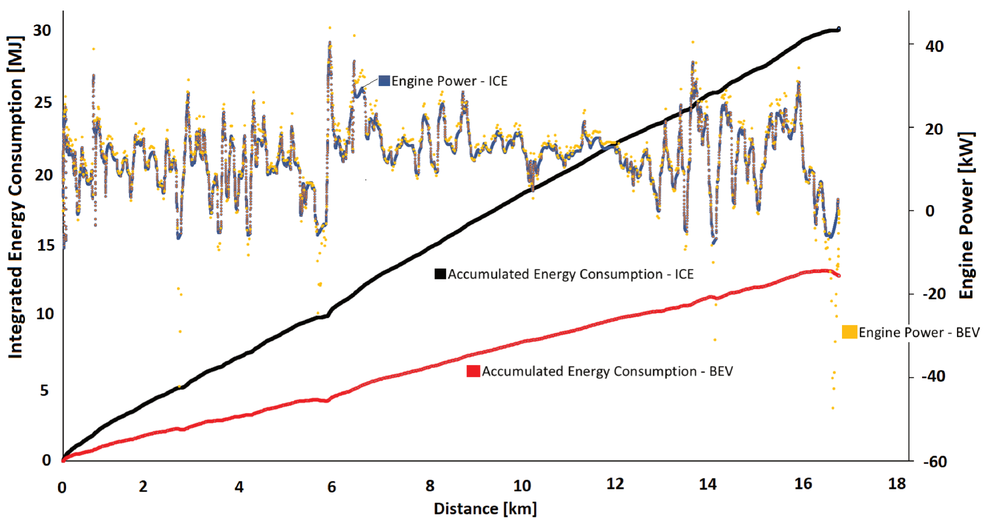

Figure 5. Integrated energy consumption for ICEV and BEV during the highway cycle.

3.2. Sankey Diagrams for Simulations Using the Brazilian Electric Mix

Overall, the electric vehicle model presented in this paper uses potential energy from the electric power generation sources (source exergy), as shown in Figures 6 and 7. Figure 6 shows the performance of this model in the FTP75 urban cycle, while Figure 7 shows a similar performance in the highway cycle. Figures are not to scale. As shown previously, electric power generation for Brazil has an estimated overall exergy efficiency of 52.3%, which is reflected in the figures by a loss of 47.7% of all potential energy in the conversion process. Then, losses by the electric vehicle (aerodynamic resistance, wheel resistance, inertia, etc.) are accounted for and are found to be higher in the highway cycle (possibly due to higher aerodynamic forces at higher speeds, as shown in Figure 3). It is also possible to realize that nearly half of all electric matrix potential (in this case, the Brazilian electric mix) is wasted in the conversion process towards electricity (47.6%). This is a reflection of the actual electric energy mix and can also be seen in other tables in this work. Other than that, it is possible to realize that most of the potential energy in the Li-ion batteries (13.2 MJ in the urban cycle) turns into work (11.6 MJ according to Table 6), which shows the effectiveness of the electric powertrain, once again, especially in the urban cycle.

On the other hand, the E22 Sankey diagrams for both driving cycles are given in Figures 8 and 9. The first conclusion of these figures is that the engine uses the highest share of energy. Remember that only a small share is turned into work, as shown in Tables 6 and 7; all the remaining energy is turned into heat and is not utilized. When applying the second law of thermodynamics, this is shown in different figures as destroyed exergy. When analyzing all the potential heat given from the E22 fuel (46.4 MJ in the urban cycle and 30.3 MJ in the highway cycle) and comparing it to the work performed, shown in Tables 6 and 7 as 9.8 MJ and 8.8 MJ, respectively, it is possible to realize the lower efficiency related to the ICEV engines and how discrepant that is from the electric vehicle analysis. Furthermore, it is possible to see how "vehicle losses" related to aerodynamic forces are also higher in the highway cycle for ICEVs, as expected.

The Sankey diagrams for the E100 model can be seen in Figures 10 and 11. It is possible to realize how little the overall picture varies from the analysis performed for the E22 model. However, as shown in Tables 6 and 7, the E100 engine appears to be slightly more efficient than the E22 engine, which is related to the factors mentioned throughout this paper.

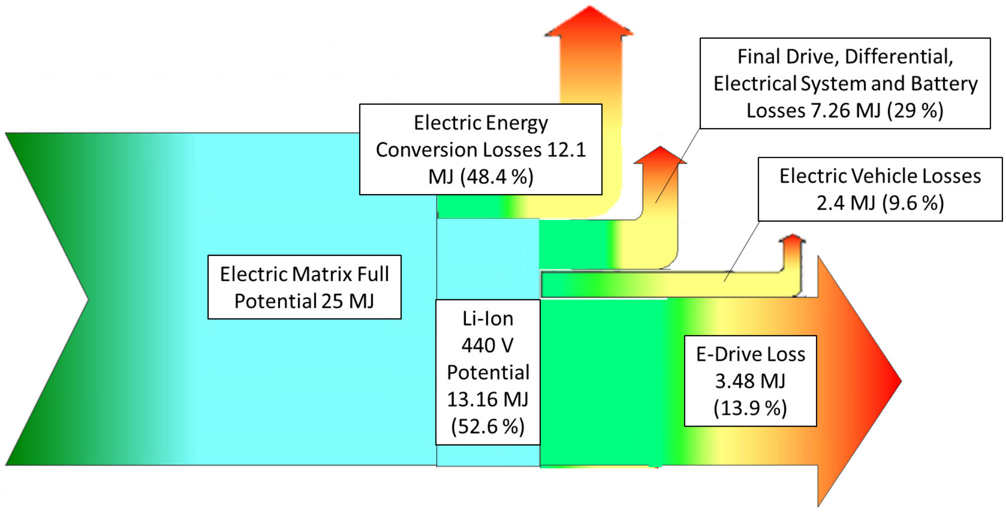

Figure 6. Sankey diagram for the EV model in FTP 75 cycle.

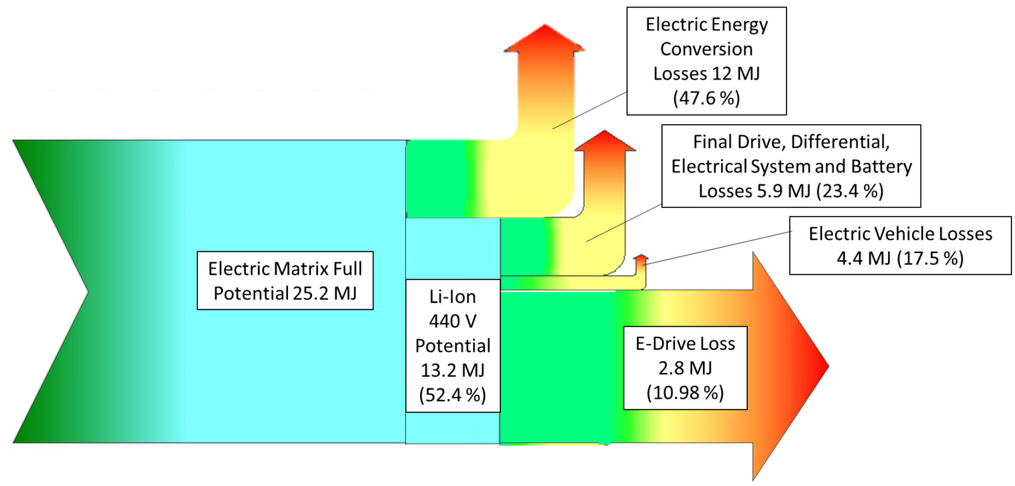

Figure 7. Sankey diagram for the EV model in Highway cycle.

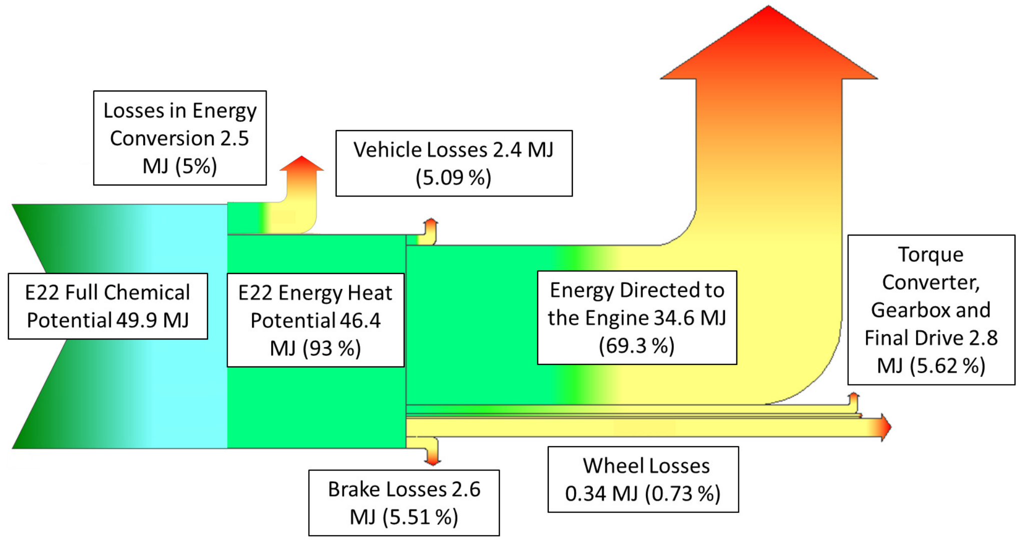

Figure 8. Sankey diagram for the E22 model in FTP 75 cycle.

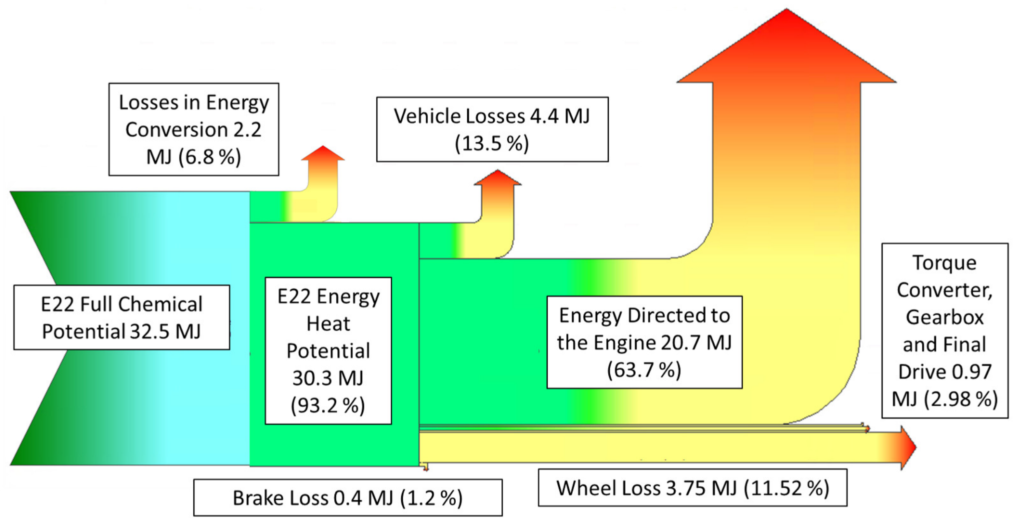

Figure 9. Sankey diagram for the E22 model in Highway cycle.

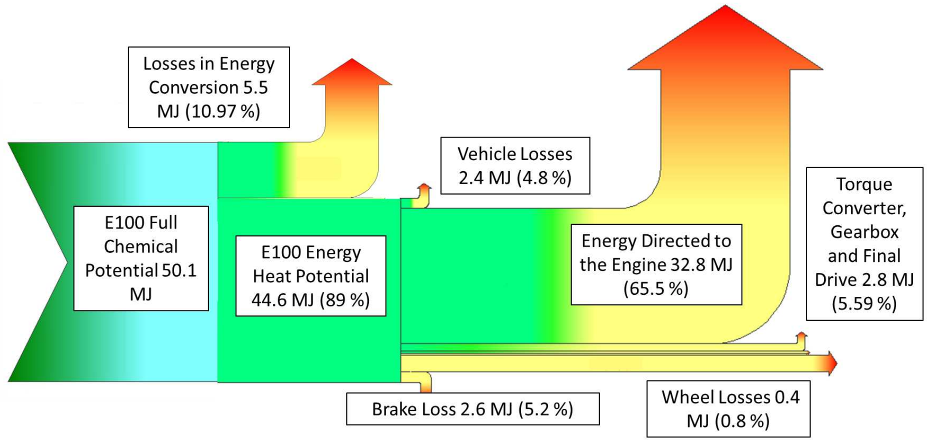

Figure 10. Sankey diagram for the E100 model in FTP 75 cycle.

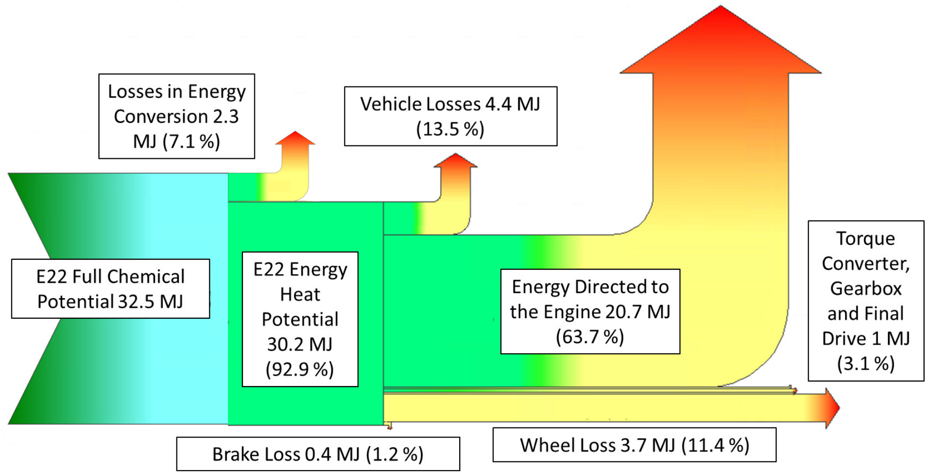

Figure 11. Sankey diagram for the E100 model in Highway cycle.

3.3. Results for FTP75 and Highway Cycles In the European Electric Mix

Nonetheless, when changing the electrical matrix from the Brazilian to the average electric mix in Europe, shown in Table 3, it is also possible to realize that the exergy input and destroyed exergy over the cycle for electric vehicles may increase due to the high usage of combustion-based electric power generation (usually fossil), which is an indication of how exergy destruction may vary as a function of the electrical mix for the location where the vehicle is charged, as seen in Table 8. Moreover, this fact is significant in Brazil, where there are populous and urban areas where energy production varies seasonally. When electricity is in peak demand, there is an increase in the electric power offered by thermoelectric stations. These particularities may decrease the advantages of BEVs over ICEVs. Moreover, when ethanol is available, there are even more variables to assess since it is less energy- and exergy-efficient than BEVs but with zero CO_2 from tank to wheel. This information must be considered in the creation of public policies to decrease taxes on electric vehicles over ethanol, for instance. This fact is more prominent when there is a change in the Brazilian tariff, named the "red tariff", where more energy is produced with fossil fuels, differently from other seasons, when energy from renewable sources is enough to cover demand.

Table 8. Results for the electric vehicle with the European electric mix.

Cycle	Electric Matrix Exergy Efficiency	Well-to-Wheel Exergy Efficiency	Exergy Consumed
City	36.65%	35.80%	35.14 MJ
Highway	36.65%	36.10%	35.40 MJ

3.4. Results for Energy Balances in FTP75 and Highway Cycles

Even though there is a substantial distinction in the presented electric mixes, there is not a comparable difference in exergy destruction for an electric vehicle in both locations. The positive impact of hydroelectric power generation in Brazil is similar to positive wind power generation and exergy efficiency in nuclear power generation in Europe (bearing in mind that the problems associated with nuclear power plants are not captured solely in these indexes), creating comparable results for the electric vehicle, even though Brazil still shows better results, as shown in Tables 6–8. These results can vary according to each electric power mix, where countries that use a higher percentage of thermoelectric power generation tend to have a higher exergy usage and destruction. The total energy consumptions for both studied vehicles are shown in Tables 9 and 10 for urban and highway cycles, respectively, considering the Brazilian electric mix. Different destroyed exergy results in each cycle refer to different energy demands for each cycle, as shown in the cycle comparison (Figure 3).

Table 9. Energy consumption in the FTP75 cycle.

Fuel	Energy Consumed	Recovered Energy	Balance	Tank-to-Wheel Efficiency
E22	46,433 kJ	-	−46,433 kJ	20.4%
E100	44,641 kJ	-	−44,641 kJ	22.0%
Electricity	15,766 kJ	3099 kJ	−12,878 kJ	71.10%

Table 10. Energy consumption in the highway cycle.

Fuel	Energy Consumed	Recovered Energy	Balance	Tank-to-Wheel Efficiency
E22	30,270 kJ	-	−30,270 kJ	29.2%
E100	30,219 kJ	-	−30,219 kJ	29.25%
Electricity	12,479 kJ	649 kJ	−12,973 kJ	72.98%

Fuel and energy consumption for both studied vehicles can be seen, in Table 11, to be compared with the INMETRO references for the same values.

Table 11. Average energy consumption.

Energy Source	Simulation Average	INMETRO Average
E22	2.2 MJ/km	2.2 MJ/km
E100	2.2 MJ/km	Not Available
Electricity	0.75 MJ/km	0.73 MJ/km

Table 9 also shows that BEVs use three times less energy than the ICEV in the urban cycle. The reasoning behind such results is related to many combustion engine power losses and unnecessary usage, such as in idling (when the vehicle is stopped and not performing any useful effect). However, this is slightly compensated for due to low-efficiency electric power generation in power stations for some of the methods shown in Table 3. When looking at Tables 9 and 10, the energy efficiency from BEVs may drop to under 50% due to lower efficiency during braking energy recovery. As seen in Table 11, the models are very well adjusted according to the INMETRO measured values for both powertrain configurations after proper model calibration. Therefore, it is understandable that exergy usage and destruction analyses are consistent with reality.

3.5. Results for CO_2 Equivalent Emissions

Equivalent CO_2 emissions can be found in Table 12, considering specific CO_2 emissions for the Brazilian energy matrix, E100, and E22 fuel, as stated in Table 5. Note that the effect of renewability is not considered in exergy efficiency. There are authors in the literature that discuss this matter, although there is still no consensus on the best indicator [52]. The most important result is that ethanol significantly impacts the decarbonization of the transport sector. It always has a lower global warming potential in equivalent CO_2 to that of electric cars in Europe. This result considers the CO_2 emissions in the whole production chain and only the fuel itself or electricity generation, without the battery production and discharge. Similar results may be found in winter, where the electric mix in regions such as São Paulo uses more thermoelectric electric energy generation with non-renewable fuels. This raises the following question for policymakers: In these seasons, is it better to fill the tank with ethanol or charge it with electricity?

Table 12. CO_2 emissions for the different cycles and fuels in Brazil and for electric cars in Europe.

Cycle	Fuel	CO_2—Brazil	CO_2—Europe
Urban	Electricity	321.96 g	1094.65 g
Urban	E22	3599.49 g	-
Urban	E100	1026.75 g	-
Highway	Electricity	321.33 g	1102.72 g
Highway	E22	2346.52 g	-
Highway	E100	695.05 g	-

By inserting the destroyed exergy, we have a single basis for comparing the different car versions and their quality of the energy conversion in symmetry with the CO_{2eq} emissions, which also places all simulations on the same basis. The exergy analysis compares different solutions employing the destroyed exergy and exergy efficiency, showing that a tank-to-wheel BEV car is more efficient than the ICEV (with direct use of the chemical exergy of the fuel) regardless of being ethanol or gasoline. We move further, considering the energy production source (electrical and chemical); the results are more challenging than expected. The electrical matrix strongly affects the exergy efficiency. Eventually, the CO_{2eq} analysis shows that one piece of information is missing—the renewability of the fuel. These pieces of information together show that a lower exergy-efficient fuel may be helpful for the transitional criteria of the car fleet and a direct reduction in the emissions by the country. Since there is a period to adapt the infrastructure for the electrification of the fleet, hopefully, this article will give new information to policymakers in these countries that already use the option of ethanol, including some EU countries.

4. Concluding Remarks

This article examines the current situation of energy and fuel in Brazil and assesses the critical distinctions between the conventional ICEV and BEV powertrains for passenger vehicles. The simulations conclude that the electric vehicle powertrain is, in both studied cycles, the urban (FTP 75) and highway, consistently more effective than the internal combustion engine powertrain during the vehicles' usage on a well-to-wheel basis. This can be seen in Tables 6 and 7, where the BEV consumes 25 MJ and 25.2 MJ of exergy, respectively, and the ICEV E22 consumes 49.9 MJ and 32.5 MJ of exergy, respectively, for a higher amount of work performed by the EV (11.6 MJ versus 9.8 MJ for the urban cycle and 9.1 MJ versus 8.8 MJ for the highway cycle) due to higher weight.

It is also possible to conclude that electric power generation might significantly affect the overall destroyed exergy in the cycle, according to the sensitivity analysis in Table 8, where the exergy consumed in the urban cycle rises from 25 MJ to 35.1 MJ, while, in the highway cycle, there is a very similar difference, from 25.2 MJ to 35.4 MJ, when compared to the results generated with the Brazilian energy mix. The results might differ even more depending on the share of nonclean electricity generation cycles, primarily due to the high exergy destroyed in combustion-based electric power generation.

The results show that ethanol E100, compared with the gasoline blend E22 in Brazil, generates at least three times fewer equivalent CO_2 emissions (1027 g CO_2, eq against 3599 g CO_2, eq for the urban cycle and 695 g CO_2, eq against 2346 g CO_2, eq for the highway cycle), whereas it generates more emissions than electric cycles in Brazil. The efficiencies are equivalent between both fuel blends in the two analyzed cycles. However, it is possible to see, in the same Table 12, that the CO_2 emissions for electric vehicles in the European electric matrix (1095 g CO_2, eq for the urban cycle and 1103 g CO_2, eq for the highway cycle) exceeds emissions from the ICEV E100 cycles (1027 g CO_2, eq for the urban cycle and 695 g CO_2, eq for the highway cycle) in both cycles, which proves that ethanol should receive more attention from public policies and incentives across the world than it currently does, even being geographically limited. Nevertheless, decarbonization appears to be more straightforward with ethanol in the transportation sector, based on the current availability of liquid fuels, while each country works on building and sustaining the correct infrastructure for electric vehicles.

The new information presented in this article compares two large areas with different types of population, technology, electrical mix, and technological development. These results are not yet present in the literature with the same focus, using robust software with city and highway cycles as a basis for the proper evaluation of emissions and the exergy destroyed. The data presented in this work can also be used for a mature cradle-to-grave analysis that also incorporates production and discards both vehicle configurations (ICEV and BEV), representing new data to corroborate the current literature, with a new analysis based on the Brazilian and EU electrical mixes and conditions.

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Abbreviations

a	Acceleration
ABNT	Associação Brasileira de Normas Técnicas/Brazilian Association of Technical Norms
ANP	Agência Nacional do Petróleo / Petroleum National Agency
b	Specific Exergy
B	Exergy
BEV	Battery Electric Vehicle
cm^3	Cubic Centimeters
CO_2	Carbon Dioxide
E	Energy
E22	Gasoline Mix with 22% Anhydrous Ethanol by Volume
E100	Hydrous Ethanol
EPA	Environmental Protection Agency
EV	Electric Vehicle
F	Force
FAME	Fatty Acid Methyl Esther
FTP	Federal Test Procedure
g	gravity
GHG	Greenhouse Gases
h	Specific Enthalpy
HP	Horsepower
ICE	Internal Combustion Engine

ICEV	Internal Combustion Engine Vehicle
J	Joule
kg	Kilogram
kWh	Kilowatt-hour
L	liter
LHV	Lower Heating Value
m	mass
m^2	Square Meters
NBR	Norma Brasileira/Brazilian Norm
PHEV	Plug-in Hybrid Electric Vehicles
Q	Heat
rpm	Rotations per minute
s	Specific Entropy
SDG	Sustainable Development Goals
T	Temperature
t	time
v	velocity
x	Position
W	Work
WtW	Well to Wheel
η	Efficiency
μ	Chemical Potential
ϕ	Ratio of Standard Chemical Exergy and Lower Heating Value
θ	Slope angle

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