# Life Cycle Emissions Analysis: Direct Comparison Between Combustion Vehicles, Using Fossil and Renewable Fuels, With Electric Vehicles

**Camilla Verbiski de Andrade**
**Murilo Artur Ortolan**
**Edvan Palioto**
**Caroline Zanata Pereira**
**Adriano Castro**
**Damian Moretti**

RENAULT

Renault do Brasil
São José dos Pinhais - PR

## ABSTRACT

The need to reduce the environmental impact of the transport sector requires knowledge of emissions throughout a vehicle's life cycle. Based on this, this study proposes to explore greenhouse gas emissions of vehicles with different propulsion modes and fuels, in terms of CO2e, through life cycle analyses already carried out. Also, it introduces a view regarding the use of pure ethanol in a light vehicle based on studies made available by Renault. The results demonstrate that the vehicle produced in Brazil, using pure ethanol, has less impact in terms of CO2e than the electric vehicle itself, even using a source of low-carbon-intensity electricity, characteristic of Brazil. The results obtained in this study contribute to the establishment of strategies and regulations aimed at decarbonizing the transport sector.

## INTRODUCTION

Carbon dioxide (CO2) emissions are one of the main causes of climate change. CO2 along with other greenhouse gases (GHG) trap solar radiation and reheat the Earth's surface. The greenhouse effect is a natural phenomenon and essential for life on planet Earth, as it maintains the average temperature of the planet. However, with the advent of the Industrial Revolution, the burning of fossil fuels, such as coal, oil and natural gas, potentiated this effect, and the increase in temperature, generating global warming, which could lead to catastrophic events, such as: more frequent and intense droughts, storms and extreme heat waves, rising sea levels, melting glaciers, loss of biodiversity and various damages to people's lives, even causing climate migrations.


Figure 1. Illustrative representation of the Greenhouse Effect
Source: [1]

With the aim of mitigating the effects of climate change on Earth, in 2015, at the United Nations Climate Change Conference, commitments were established through the Paris Agreement to move towards carbon neutrality in this century. In this agreement, Brazil assumed the commitment to reduce greenhouse gases by up to 50% in 2030, compared to 2005 levels [2].

The transport sector is one of the main agents in greenhouse gas emissions. Emissions from this sector grew at an average annual rate of 1.7% between 1990 and 2021, since its energy consumption comes predominantly from non-renewable sources [3], [4]. Road transport alone accounts for 45% of global oil demand [5].

## BRAZILIAN SETTING

THE TRANSPORT SECTOR - Although energy demand in Brazil is supplied predominantly by non-renewable sources, its percentage is below world levels. In 2019, biofuels provided around 3% of the global fuel demand for road transport [6]. In Brazil, the share of renewable fuels corresponds to 23% in the entire transport sector, of which 17.4% and 5.2% correspond to ethanol and biodiesel, respectively [7].

Despite the significant share of biofuel use, the transport sector in Brazil is responsible for the largest share of anthropogenic CO2 emissions associated with energy [7]. It is estimated that the road sector accounts for around 7.8% of total CO2 emissions [8].

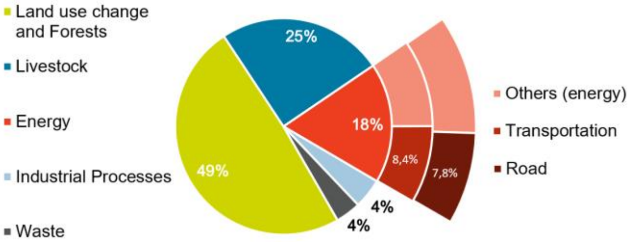



Figure 2. Total CO2 emissions in Brazil by sector
Source: SEEG adaptation [4]

Passenger vehicles account for approximately 2.6% of CO2e emissions in Brazil, according to SEEG 2021 data [8]. Through estimates related to production, logistics, recycling and vehicle use, it is understood that, in the country, this pollutant is mostly generated during the phase we call well-to-wheel (WTW), occupying around 90% of emissions associated with passenger vehicles. The other 10% is associated with the remaining stages of a car's life cycle. This is due to the fact that the country still has a very old fleet, where only 22.7% of the car fleet has an average age of up to 5 years [9], equipped with combustion engines virtually in its entirety. But when we look at production, we are talking about a much smaller number of vehicles, close to 2 million cars per year [10]. Also noteworthy is the fact that there is still no local production of batteries, which contributes to reduced CO2e in production.

ETHANOL - Ethanol stands out as a fuel due to its high octane rating and high latent heat of vaporization, allowing higher compression rates and an increase in resistance to knocking [11].

Brazil is the second largest producer of ethanol in the world and the first producer of sugarcane-based ethanol [12]. Demand and supply of this biofuel are expected to grow at an annual rate of 4.2% and 4.1% by 2032, respectively [13]. However, for ethanol to remain a sustainable solution for replacing fossil fuels, it is necessary that the farmland used for the expansion of its production does not come from deforestation [14]. With the insertion of 2G ethanol, there is no need to increase the cultivation area, since it is generated from by-products of 1G ethanol and sugar, thus making the production of this biofuel even more sustainable [15].

The development of the sugar and alcohol industry for the production of ethanol took place with the institution of the Procalcool program, in 1975. With the first major oil crisis, due to the need for energy security and economic issues, the creation of this program aimed at introducing ethanol as a vehicle fuel. Still, the great advance in automotive engineering took place from 1979 through this program with the launch of vehicles powered solely by ethanol. Another technological leap in the country was the introduction of cars with flex-fuel engines, starting in 2003, boosting the use of this biofuel [16], [17]. In 2023, in Brazil, flex-fuel vehicles should have a share of 83% in the Otto cycle fleet [18].

The majority presence of flex-fuel vehicles in the fleet, sovereignty in sugarcane-based production, mastery of technology and large-scale consumption make ethanol a potential for mitigating greenhouse gas emissions in Brazil. ANFAVEA, the National Association of Motor Vehicle Manufacturers, envisages an acceleration in decarbonization in the short-medium term through increased ethanol consumption, so that, under the scenario of ethanol consumption representing 61% in 2035, it is projected a reduction of approximately 15% in CO2 emissions from the light vehicle fleet compared to the same year under an inertial scenario [19].

## POLICIES

There are countless policies around the world that regulate and control emissions in the various phases of the vehicle cycle, as can be seen in the figure below. We are talking about controls related to production, related to carbon markets associated with the production of the pollutant, control of CO2e at borders, when components are produced abroad and imported, as well as specific regulations on more expensive components. CO2 is also controlled when vehicles are sold. Numerous fees, incentives or even banishment policies are in practice around the world.

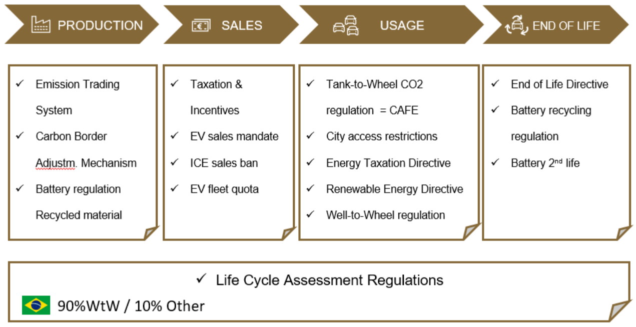



Figure 3. Policies that regulate emissions throughout a vehicle's life cycle
Source: own authorship

Today, the path towards decarbonizing the transport sector in Brazil is based on the development and encouragement of the use of fuels with low carbon intensity and greater vehicle energy efficiency. The Rota 2030

Program regulates the energy efficiency of vehicles and encourages the development and competitiveness of the automotive sector in the country. In 2022, fuel consumption in new vehicles was reduced, reaching the target of 11% compared to the efficiency values between 2017 and 2021 [20]. Regarding the control of vehicle emissions into the atmosphere, the Air Pollution Control Program for Motor Vehicles (PROCONVE) defines targets that gradually limit these emissions. Together with the Air Pollution Control Program for Motorcycles, Mopeds and Similar Vehicles (PROMOT), a reduction of up to 98% in pollutant emissions per vehicle is observed [21].

Still, in order to stimulate and expand the production of biofuels and achieve CO2 emission reduction targets, in Brazil, the National Biofuel Policy, RenovaBio, was created [22]. Through the Decarbonization Credit (CBIO), where each CBIO corresponds to a ton of CO2 not emitted into the atmosphere, more than 30 million tons of CO2 were avoided in 2021 [23].

Even with the benefit of the Brazilian energy matrix being made up of almost 83% of renewable sources [24], targets for electrification of the road fleet have not yet been implemented in the country. Brazil does not have the same urgency to reduce pollutant emissions as other countries that need to accelerate the electrification of the transport sector. Even with the significant growth in sales of electric vehicles in Brazil, reaching a 300% increase in sales of battery electric vehicles between 2021 and 2022, there are obstacles that hinder the insertion of electric vehicles, such as the high cost of the vehicle, low autonomy batteries and little charging infrastructure [25].

Decision-making aimed at more sustainable mobility through regulations and political initiatives and market strategies by vehicle manufacturers, fuel producers and distributors can be based on the analysis of a vehicle's life cycle. Life Cycle Assessment (LCA) is a tool capable of analyzing the environmental impacts of a given technology and comparing it with other alternatives [26]. More details about this assessment method will be covered in the next chapters.

## LIFE CYCLE ASSESSMENT OF A VEHICLE

Life Cycle Assessment comprises a holistic analysis of the environmental impacts of a product or process throughout its entire life cycle. Based on ISO 14040 and 14044 standards, the LCA is structured in 4 stages: definition of goals and scope, inventory analysis, impact assessment and interpretation [27].

This assessment tool covers several categories of environmental impacts, such as climate change, ecotoxicity, depletion of natural resources, land acidification, etc. A metric widely used to assess impacts on climate change is carbon dioxide equivalent (CO2e), which is the result of multiplying the tons emitted by each greenhouse gas by its respective global warming potential. In this work, the greenhouse gas emissions of vehicles with different propulsion modes and fuels will be explored in terms of kg CO2e/km through a life cycle analysis already carried out.

The lifecycle of a vehicle encompasses the production, use and end-of-life phases. Production relates all emission aspects within automobile and auto parts factories, as well as the associated logistics from production to the sale of the vehicle. The use phase, also called well-to-wheel (WTW), deals with emissions in the production of the fuel/energy source, up to the direct CO2 emission carried out by the vehicle. This phase can be subdivided into the well-to-tank (WTT) and tank-to-wheel (TTW) phases, which consider emissions from fuel or electricity production and direct emissions from vehicle use, respectively. The balance of emissions associated with vehicle recycling is also included in the calculation of CO2 in the life cycle.

$$\mathrm{CO_2e} = \mathrm{CO_2eq} + \left[\frac{\mathrm{gCO_2eq}}{\mathrm{Mj}} \times \frac{\mathrm{Mj}}{\mathrm{km}}\right] \times \mathrm{km} + \mathrm{CO_2eq}$$

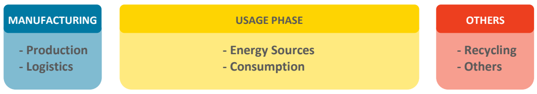



Figure 4. Calculation of the LCA concept
Source: [1]

Next, a brief review of life cycle analyses in the literature and their implications will be addressed.

## STUDIES

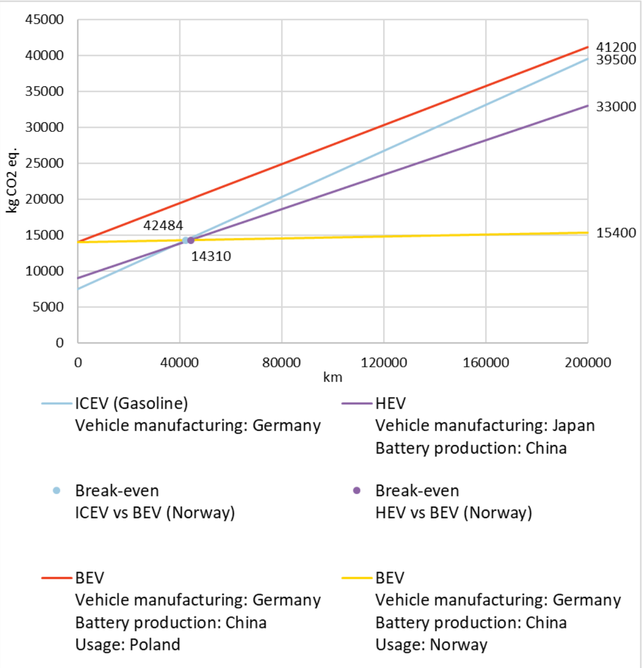
Studies of the Life Cycle Assessment of a vehicle are extensive in the literature. These studies mainly address comparisons between different types of vehicle segments, engine technologies, batteries, fuels, production sites and vehicle use, among others.

The life cycle analysis carried out by [20] details the contribution to CO2 emissions of the main modules and materials during the production of internal combustion engine (ICE), hybrid electric and battery electric vehicles. In this study, it is shown that the battery system in a battery electric vehicle (BEV) has the highest carbon footprint during its production compared to other vehicle modules, since its manufacture is highly polluting. The carbon footprint of producing battery electric vehicles can be 50-100% higher compared to a conventional vehicle [20]. [22] compares the lifecycle emissions of internal combustion engine vehicle (ICEV) and electric vehicle (EV), with reference to BEVs, from different segments under various scenarios. The table below shows the CO2 emissions from the production of A-segment and EV and ICEV in four countries with different levels of energy matrix emission intensity. Note that emissions from battery manufacturing represent more than 50% of total vehicle production.

Table 1. CO2 emissions in the vehicle and battery production phase (gCO2/km)
Source: adaptation [22]

| | EV | | ICEV |
|---|---|---|---|
| **Country** | Production of other components and assembly of the vehicle | Battery production | Production of other components and assembly of the vehicle |
| **China** | 33.31 | 19.41 | 36.55 |
| **Germany** | 20.65 | 12.04 | 22.66 |
| **USA** | 20.91 | 12.19 | 22.94 |
| **Italy** | 16.04 | 9.35 | 17.60 |

Not only in production, the intensity of emissions from the energy matrix, in which the vehicle is inserted, interferes with pollutant levels in the use phase. [27] exposes that, consuming energy from an extremely polluting source and another mostly renewable source, such as Poland (682 gCO2e/kWh) and Norway (35gCO2e/kWh), respectively, the WWT CO2e emissions of a compact battery vehicle result in 136 gCO2e/km and 7 gCO2e/km, respectively. The graph below illustrates emissions in these two usage scenarios and compares with internal combustion and hybrid vehicles. The analysis carried out by [28] concludes that, for a battery electric vehicle to emit less CO2 compared to a conventional vehicle throughout its life cycle, the average intensity of CO2 in the production of electricity must be around 320g/kWh. The life cycle analysis of vehicles from a perspective of projecting the energy matrix of several countries can be seen in [29].



Graph 1. Emissions over the life cycle of vehicles with different powertrains and battery vehicles with use phases under different electrical matrices
Source: adaptation [27]

The use phase emissions of a vehicle depend on the mode of propulsion and the fuel or source of electricity for charging. [30] analyzes the life cycle of C-segment vehicles considering the above factors. In this study, it is evident that emissions in the WTW phase using non-renewable fuels significantly impact the sustainability of conventional vehicles, representing more than 50% of emissions over the life cycle. However, the use of biofuels can reduce impacts during the use phase. In [31], it is noted that the compact conventional or hybrid vehicle using ethanol from cellulose has lower emission levels than a battery electric vehicle charging from the EU-28 energy matrix.

In Brazil, there are few studies related to the life cycle of vehicles. [32] compares the environmental impacts of the life cycle of internal combustion vehicles using E27, E100 and the E27/E100 mixture, battery electric and plug-in hybrid vehicles from the perspective of use in the country. In this study, it was shown that battery electric vehicles have the lowest environmental impact, followed by conventional vehicles powered by ethanol. The latter, however, has the lowest global warming potential (GWP).

[33] evaluates the life cycle of two fuel cell vehicle models. Current vehicles with internal combustion engines using ethanol have been shown to have the lowest global warming potential compared to these projected powertrain technologies in 2030, assuming that the farmland for ethanol production does not come from deforestation.

[26] compares the sustainability of a fleet mainly composed of electric vehicles and another fleet using ethanol in Brazil. In a TTW approach, the use of ethanol proves to be a convenient and sustainable solution for reducing pollutant emissions. However, within the WTW analysis, fleet electrification becomes advantageous since ethanol production tends to be emission intensive.

[34] addresses the implementation of electric vehicles in the Brazilian fleet, consolidating information that exposes the Brazilian panorama of electrification of transport, which points to the need to set well-defined policies for the insertion of electromobility in the country.

That said, with proper land use management, more efficient sugarcane production and greater vehicle efficiencies lead to establishing ethanol as the most sustainable solution for Brazil [26], thus depending on policies that regulate its production in order to minimize environmental impacts.

The life cycle study to be presented below corroborates the conclusions found in the literature. This study is limited to the analysis of CO2e emissions from the life cycle of vehicles with different propulsion modes, manufactured in different countries and using different fuels.

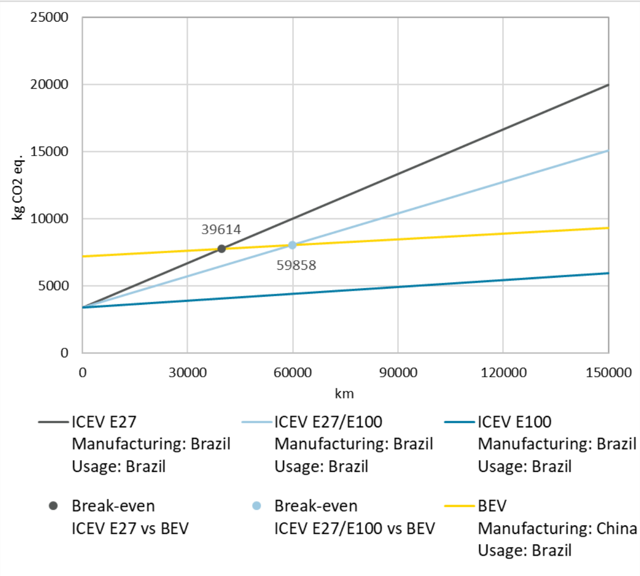
**CASE RENAULT**

Renault S.A. develops life cycle analyses of its products in accordance with ISO 14040 and ISO 14044 standards. Based on these analyses, this study will address the comparison of the life cycle of compact SUV vehicles with conventional engine (internal combustion) and electric motor in function of CO2 equivalent emissions. The main assumptions used in these analyses are presented below.

The ICEV is produced in Brazil and the BEV, as well as its battery, are manufactured in China. The location of production was considered for the calculation of emissions from materials and manufacturing. The use phase is set at 150,000 km, on which the WTW emission assessment is based. In this phase, the operation and maintenance of the automobile are considered. End-of-life emissions data are included in the production phase.

Also, for the WTW analysis, vehicles with conventional engines were evaluated under two fuels, gasoline E27 and E100, commercially sold in Brazil, and under the mixture of these two fuels. Since there are no TTW emissions from electric vehicles, the WTT analysis was carried out from the perspective of emissions from the Brazilian energy matrix.

The results of these analyses are shown in the graph below. It is noticed that the emissions in the production of the electric vehicle almost double in comparison to the production of the ICE vehicle, since the contribution of the manufacture of batteries in these emissions is significant.

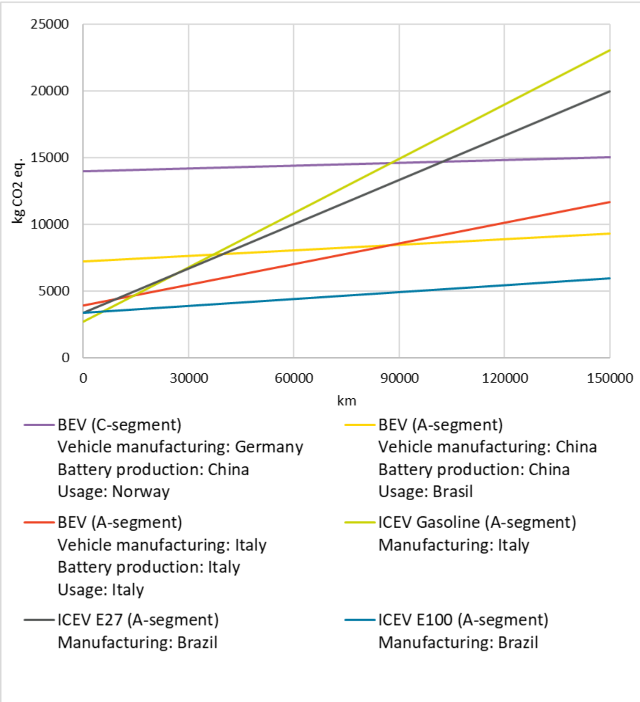



Graph 2. Emissions over the life cycle of ICE vehicles, under different fuels in the use phase, and BEV
Source: Renault adaptation

Analyzing the vehicle use phase, it is noted that ICE vehicles, operating under E27 and E27/E100, become more polluting as the distance traveled increases. The break-even point using E27 is close to 40,000 km, and with the E27/E100 mixture the point is close to 60,000 km. However, there is no intersection of the curves of electric and ICE vehicles using pure ethanol, so that, from the perspective of use in Brazil, conventional vehicles operating with E100 will emit less CO2e over its lifetime compared to BEV.

The graph below compares the results obtained by the Renault study with articles [27] and [35]. It is noticed that, despite having the highest level of emission in its manufacture, the battery electric vehicle produced in China and with its use phase in Brazil has the lowest emission at the end of its useful life compared to vehicles of the same model of propulsion with manufacture and use in different countries. This is due to the clean generation of electricity in Brazil, in which more than 80% of the Brazilian energy matrix comes from renewable sources.

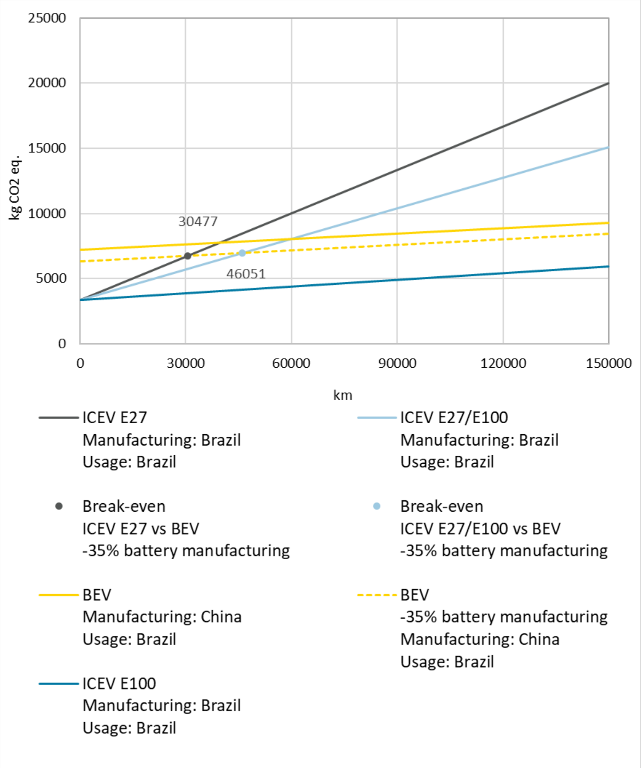
In this comparison, the conventional vehicle produced in Brazil and using pure ethanol also stands out as the solution with the lowest level of CO2e at the end of its useful life. This is due to the significant use of sugarcane-based ethanol in the light vehicle fleet, a biofuel with the lowest carbon footprint in the world based on this raw material [15].




Graph 3. Comparison between life cycle analyses
Source: Renault adaptation, [27] and [35]

VISION IMPROVEMENT IN ELECTRIFICATION - BEV batteries have a usage phase of approximately 150,000 km. If we consider an electric vehicle with a useful life greater than 150,000 km, it will need to be replaced. Consequently, there will be an increase in emissions over the lifecycle of the vehicle. This is exposed in the study by [36], where the impact of replacing the battery on the GHG emissions of a compact vehicle with a use phase of 200,000 km was analyzed. For an energy matrix of intensity 0.024 kg eq.CO2/kWh, replacing the battery of a BEV results in an increase in emissions of more than 30% at the end of the vehicle's life cycle [36]. In this same study, the capacity and, consequently, the size of the batteries also interfere with their production emissions. For the same energy matrix intensity value, increasing the battery from 30 kWh to 85 kWh results in a 47% increase in the total emissions of a battery vehicle.

Given the significant impact of batteries over the life cycle of a vehicle, a 35% reduction in CO2 emissions from battery manufacturing is projected, an objective set by the Renault Group to be achieved by 2030. However, it is observed that conventional vehicles using E100 biofuel remains the scenario with the lowest CO2e emissions throughout their entire life cycle, as can be seen in the graph below.




Graph 4. CO2e emissions over the life cycle of a battery electric vehicle, considering a 35% reduction in emissions during battery production, and a vehicle with an internal combustion engine using different fuels
Source: Renault adaptation

This indicates that, despite the fact that the Brazilian energy matrix is mostly derived from renewable sources, the ethanol biofuel can be an alternative for mitigating WTW GHG emissions in the short and medium term.

## CONCLUSION

Life cycle analysis helps in decision making and in the development of policies and strategies that minimize the environmental impacts caused by a given product or process. In this research, the study of the life cycle, carried out by Renault, of two models of vehicles with different types of engine and different types of fuel was approached. The study showed that a conventional vehicle using pure ethanol has lower levels of greenhouse gas emissions at the end of its useful life compared to an electric vehicle operating in Brazil. Furthermore, with a 35% reduction in emissions from the electric vehicle battery production, the internal combustion vehicle running on pure ethanol remains the solution with the lowest CO2 eq. at the end of the life cycle.

However, full electric vehicles remain with a very good score of life cycle CO2e emissions compared to ICE filled with fossil fuels. Also, other constraints as local pollutant emissions, as hydrocarbons (HC) and nitrogen oxides (NOx), acoustic pollution and drivability are key points for full electric empowerment.

In conclusion, the insertion of electrification in the fleet is foreseen for the coming decades and, together with an increase in the use of ethanol, will make the Brazilian transport sector reach carbon neutrality much faster than other regions.

The results shown here are in line with life cycle analyses found in the literature and contribute to the establishment of strategies and regulations aimed at decarbonizing the transport sector.

## REFERENCES

[1] M. A. Ortolan, C. Z. Pereira, E. Palioto, E. L. Silva, G. N. Sampaio, and D. Moretti, "Análise da Neutralidade de Carbono do Poço-À-Roda sobre o Setor Automotivo," *Anais do XXIX Simpósio Internacional de Engenharia Automotiva*, pp. 340-359, 2022, doi: 10.5151/simea2022-PAP64.

[2] BBC News Brasil, "COP26: Brasil promete reduzir emissões pela metade até 2030 e zerar desmatamento 2 anos antes." https://www.bbc.com/portuguese/brasil-59065366 (accessed Mar. 27, 2023).

[3] IEA, "Transport," 2022.https://www.iea.org/reports/transport (accessed Feb. 01, 2023).

[4] IEA, "Total final energy consumption in the transport sector in the Net Zero Scenario, 2010-2030." https://www.iea.org/data-and-statistics/charts/total-final-energy-consumption-in-the-transport-sector-in-the-net-zero-scenario-2010-2030 (accessed Feb. 01, 2023).

[5] OPEC, “World Oil Outlook 2020,” 2020. Accessed: Feb. 01, 2023. [Online]. Available: https://www.opec.org/opec_web/en/publications/3049.htm

[6] IEA, “Energy Technology Perspectives 2020,” Paris. Accessed: Feb. 03, 2023. [Online]. Available: https://www.iea.org/reports/energy-technology-perspectives-2020

[7] EPE, “Balanço Energético Nacional 2022: Ano base 2021,” Rio de Janeiro, 2021. Accessed: Feb. 01, 2023. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2022

[8] SEEG, “Emissões.” https://plataforma.seeg.eco.br/ (accessed Feb. 10, 2023).

[9] Sindipeças, “Relatório da Frota Circulante,” 2022. https://www.sindipecas.org.br/area-atuacao/?co=s&a=frota-circulante (accessed May 14, 2023).

[10] ANFAVEA, “Anuário da Indústria Automobilística Brasileira,” 2022. Accessed: May 14, 2023. [Online]. Available: https://anfavea.com.br/site/anuarios/

[11] A. C. T. Malaquias, N. A. D. Netto, F. A. R. Filho, R. B. R. da Costa, M. Langeani, and J. G. C. Baêta, “The misleading total replacement of internal combustion engines by electric motors and a study of the Brazilian ethanol importance for the sustainable future of mobility: a review,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, no. 12. Springer Verlag, 2019. doi: 10.1007/s40430-019-2076-1.

[12] UNICA, “Sugarcane Sector.” https://unica.com.br/en/sugarcane-sector/ (accessed Mar. 27, 2023).

[13] EPE, “Plano Decenal de Expansão de Energia 2032 - Oferta de Biocombustíveis,” 2022. Accessed: Mar. 27, 2023. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2032

[14] A. Alkimim and K. C. Clarke, “Land use change and the carbon debt for sugarcane ethanol production in Brazil,” *Land use policy*, vol. 72, pp. 65-73, 2018, doi: 10.1016/j.landusepol.2017.12.039.

[15] UNICA, “Etanol.” https://unica.com.br/setor-sucroenergetico/etanol/ (accessed Mar. 27, 2023).

[16] ANFAVEA, “Proalcool.” https://anfavea.com.br/site/o-que-foi-o-proalcool/ (accessed Mar. 28, 2023).

[17] A. A. Soares and J. C. Z. Junior, “O Brasil como grande player no mercado mundial de etanol,” *Revista de Política Agrícola*, 2021, Accessed: Mar. 14, 2023. [Online]. Available: https://seer.sede.embrapa.br/index.php/RPA/article/view/1649

[18] EPE, “Demanda de energia de veículos leves,” Accessed: Mar. 28, 2023. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/demanda-de-energia-dos-veiculos-leves

[19] ANFAVEA, “O caminho da descarbonização do setor automotivo no Brasil,” 2021. https://anfavea.com.br/site/estudos-e-apresentacoes/ (accessed Mar. 11, 2023).

[20] Ministério da Economia, “Rota 2030 - Mobilidade e Logística,” 2020. https://www.gov.br/produtividade-e-comercio-exterior/pt-br/assuntos/competitividade-industrial/setor-automotivo/rota-2030-mobilidade-e-logistica (accessed Feb. 26, 2023).

[21] Ibama, “Programa de controle de emissões veiculares (Proconve),” 2022. https://www.gov.br/ibama/pt-br/assuntos/emissoes-e-residuos/emissoes/programa-de-controle-de-emissoes-veiculares-proconve (accessed Feb. 26, 2023).

[22] ANP, “Renovabio,” 2020. https://www.gov.br/anp/pt-br/assuntos/renovabio (accessed Feb. 26, 2023).

[23] ANP, “Painel Dinâmico da Plataforma CBIO,” 2021. https://www.gov.br/anp/pt-br/centrais-de-conteudo/paineis-dinamicos-da-anp/paineis-dinamicos-do-renovabio/painel-dinamico-da-cbio (accessed Feb. 26, 2023).

[24] EPE, “Matriz Energética e Elétrica.” https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica (accessed Mar. 27, 2023).

[25] EPE, “Plano Decenal de Expansão de Energia 2032 - Eletromobilidade.” Accessed: Mar. 27, 2023. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2032

[26] L. M. M. Benvenutti, L. M. de S. Campos, D. Vazquez-Brust, and C. Liston-Heyes, “Electric versus ethanol? A fleet-based well-to-wheel system dynamic model for passenger vehicles,” *Transp Res D Transp Environ*, vol. 115, 2023, doi: 10.1016/j.trd.2023.103604.

[27] M. Hirz and T. T. Nguyen, “Life-Cycle CO2-Equivalent Emissions of Cars Driven by

Conventional and Electric Propulsion Systems," *World Electric Vehicle Journal*, vol. 13, no. 4, 2022, doi: 10.3390/wevj13040061.

[28] G. Zheng and Z. Peng, "Life Cycle Assessment (LCA) of BEV's environmental benefits for meeting the challenge of ICExit (Internal Combustion Engine Exit)," in *Energy Reports*, Elsevier Ltd, 2021, pp. 1203-1216. doi: 10.1016/j.egyr.2021.02.039.

[29] M. Shafique and X. Luo, "Environmental life cycle assessment of battery electric vehicles from the current and future energy mix perspective," *J Environ Manage*, vol. 303, 2022, doi: 10.1016/j.jenvman.2021.114050.

[30] C. Ternel, A. Bouter, and J. Melgar, "Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030," *Transp Res D Transp Environ*, vol. 97, 2021, doi: 10.1016/j.trd.2021.102897.

[31] D. C. Rosenfeld, J. Lindorfer, and K. Fazeni-Fraisl, "Comparison of advanced fuels—Which technology can win from the life cycle perspective?," *J Clean Prod*, vol. 238, 2019, doi: 10.1016/j.jclepro.2019.117879.

[32] L. L. P. de Souza, E. E. S. Lora, J. C. E. Palacio, M. H. Rocha, M. L. G. Renó, and O. J. Venturini, "Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil," *J Clean Prod*, vol. 203, pp. 444-468, 2018, doi: 10.1016/j.jclepro.2018.08.236.

[33] J. E. Velandia Vargas and J. E. A. Seabra, "Fuel-cell technologies for private vehicles in Brazil: Environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles," *Science of the Total Environment*, vol. 798, 2021, doi: 10.1016/j.scitotenv.2021.149265.

[34] J. E. V. Vargas, J. E. A. Seabra, C. K. N. Cavaliero, A. C. S. Walter, S. P. Souza, and D. G. Falco, "The new neighbor across the street: An outlook for battery electric vehicles adoption in Brazil," *World Electric Vehicle Journal*, vol. 11, no. 3. MDPI AG, 2020. doi: 10.3390/WEVJ11030060.

[35] S. Franzò and A. Nasca, "The environmental impact of electric vehicles: A novel life cycle-based assessment framework and its applications to multi-country scenarios," *J Clean Prod*, vol. 315, 2021, doi: 10.1016/j.jclepro.2021.128005.

[36] M. Kannangara, F. Bensebaa, and M. Vasudev, "An adaptable life cycle greenhouse gas emissions assessment framework for electric, hybrid, fuel cell and conventional vehicles: Effect of electricity mix, mileage, battery capacity and battery chemistry in the context of Canada," *J Clean Prod*, vol. 317, 2021, doi: 10.1016/j.jclepro.2021.128394.

**APPENDIX**

Disclaimer

"Renault Group provides the public life cycle assessment reports for its products. The methodology developed by Renault Group and the calculation results presented in these reports are systematically subjected to a critical review by a third party in order to guarantee their compliance with ISO14040 and 140444 standards.

The results presented in this document are based on the same Renault Group LCA methodology but have not been validated by an external critical review.

Under no circumstances should these results be compared with LCA results from other sources, as comparisons between LCA calculations are only relevant if the methodology and data sources are completely homogeneous (definition of the perimeter covered, functional unit, process modelling, impact calculation method, primary and secondary data sources, cut-off criteria, etc.)."