Pontifícia Universidade Católica
do Rio de Janeiro

**Heinrich Gustave Herzog**

# Assessing the impact of electrification on decarbonisation of the road transportation segment in Brazil by 2050

**Dissertação de Mestrado**

Dissertation presented to the Programa de Pós-graduação em Engenharia Urbana e Ambiental of PUC-Rio in partial fulfilment of the requirements for the degree of Mestre em Engenharia Urbana e Ambiental.

Prof. Dr. Rodrigo Flora Calili
Prof. Dr. Maria Fatima Ludovico de Almeida

Rio de Janeiro
October 2nd, 2024

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## Abstract

Herzog, Heinrich Gustave; Calili, Rodrigo Flora (Advisor); Almeida, Maria Fatima Ludovico de (Co-advisor). **Assessing the Impact of Electrification on Decarbonisation of the Road Transportation Segment in Brazil by 2025.** Rio de Janeiro, 2024. 156 p. Dissertação de Mestrado – Departamento de Engenharia Civil e Ambiental, Pontifícia Universidade Católica do Rio de Janeiro.

The electrification of the light vehicle fleet is a key strategy for mitigating greenhouse gas emissions from the road transportation segment. This dissertation assesses the potential impact of electrifying Brazil's light vehicle fleet by 2050, employing a prospective methodology to build alternative decarbonisation scenarios, combining foresight and forecasting approaches. The research has two main objectives: (i) to estimate the potential reduction in greenhouse gas emissions from fleet electrification by 2050 in Brazil across different decarbonisation scenarios, and (ii) to analyse the barriers to implementation in each scenario, along with their implications for key stakeholders. The findings indicate that electrification has significant potential to enhance the decarbonisation of Brazil's light vehicle fleet, with estimated greenhouse gas emission reductions ranging from 7.0% in the least ambitious scenario to 25.7% in the most ambitious scenario by 2050. This study concludes that decarbonising Brazil's light vehicle fleet will require a coordinated, multi-stakeholder approach to overcome these challenges and implement effective strategies. It also offers valuable insights for future research and policy development aimed at achieving significant emissions reductions through fleet electrification by 2050.



### Keywords

Road transportation; electrification; decarbonisation; greenhouse gas emission reduction; prospective scenario modelling; morphological analysis; Brazil.

## Extended Abstract


### Introduction

As countries strive to fulfil their commitments to mitigate climate change and limit global warming to below 2°C, the transportation sector remains one of the most important, responsible for approximately one-sixth of total global greenhouse gas (GHG) emissions. Within this sector, road transport represents 45% of global oil demand and generates 76% of transportation emissions, with light-duty vehicles (LDVs) comprising the largest share.

Electrification of LDVs is widely recognized as critical for decarbonisation. Brazil stands out globally due to its high share of renewable electricity (88% in 2022) and its mature ethanol sector, which have provided comparatively low-carbon mobility options even as adoption barriers remain high for electric vehicles (EVs).

This study addresses two pivotal questions:

1. To what extent can electrification enhance the decarbonisation of Brazil's LDV fleet by 2050?
2. What barriers must be overcome to achieve successful LDV fleet electrification in Brazil by 2050?

To answer these, an integrated framework is developed that combines foresight and forecasting to build prospective scenarios — a methodological advance that addresses a key research gap in the relevant literature. The study's findings offer valuable guidance for Brazil's ongoing energy transition and for other countries with similar energy profiles.

## Literature Review

While the transition to electric mobility is widely considered essential, the pathway for Brazil is far from straightforward. On the one hand, the country's clean electricity grid dramatically increases the GHG mitigation benefits of BEVs compared to fossil-fuel-dominated grids elsewhere. On the other hand, the prevalence of ethanol-fuelled flex vehicles provides an alternative decarbonisation route and creates competition for policy focus and infrastructure investment.

The literature reveals a persistent gap: the absence of fully integrated analytical frameworks capable of concurrently modelling technological, economic, policy, and social variables, and able to incorporate scenario planning, structural analysis, and forecasting. This is significant for Brazil, given the highly contextual dynamics between renewable power, ethanol, and vehicle technology.

## Methodology

In response to the aforementioned gap, a multi-stage, mixed-methods framework is proposed, composed of:

1. **Guiding Question and Time Horizon**: Anchored in national (PNE 2050) and global ("Net Zero 2050") targets.
2. **Key Variable Identification and Structural Analysis**: Using expert workshops and MICMAC software to classify driving, relay, regulatory, and resulting variables.
3. **Identification of Stakeholders**: Comprehensive identification of influencers ranging from government agencies to private electricity, auto, ethanol, financing, and consumer entities.

4. **Current Context and Trend Assessment**: Evaluation of current fleet composition, energy mix, and socio-economic drivers.
5. **Scenario Construction via Morphological Analysis**: Systematic generation of consistent decarbonisation scenarios, based on Zwicky's General Morphological Analysis and informed by empirical and theoretical insights.
6. **Fleet Growth and Emissions Modelling**: Regression-based projections leveraging historical data on population, GDP, vehicle sales patterns, and energy consumption, combined with scenario-specific shares of ICEVs, HEVs, PHEVs, BEVs, and flex-fuel vehicles.
7. **Detailed Scenario Narratives (2025–2050)**: Analysis of trajectories segmented into near (2025–2030), mid (2031–2040), and long-term (2041–2050) periods.
8. **Barrier Analysis**: Categorization and analysis of sixteen implementation barriers (regulatory, technical, economic, social, industrial, environmental), linked to specific variables and actors.

## Scenario Modelling

Five prospective scenarios for Brazil's LDV fleet by 2050 are constructed:

- **Scenario A:** Low decarbonisation, low electrification.
- **Scenario B:** Moderate decarbonisation, low electrification.
- **Scenario C:** High decarbonisation, moderate electrification.
- **Scenario D:** High decarbonisation, moderate electrification with ethanol.
- **Scenario E:** High decarbonisation, high electrification.

All scenarios employ quantitative projections of:

- Fleet growth and composition by technology.
- Average fuel/electricity consumption rates.
- Annual mileage.
- Emissions by fuel type (gasoline, ethanol, electricity).
- Total and accumulated GHG emission reductions over 2025–2050.

## Results and Key Findings

Accumulated GHG reductions (over BAU) by 2050:

- Scenario A: 7.0%
- Scenario B: 8.8%
- Scenario C: 12.8%
- Scenario D: 21.3%
- Scenario E: 25.7%

Sixteen major barriers are identified:

- **Regulatory**: Lack of clear ICEV phase-out dates, weak policy incentives for EV adoption and manufacturing.
- **Technical**: Insufficient charging infrastructure, grid limitations, BEV technology gaps (range, charging time).
- **Economic**: High BEV upfront costs, uncertain resale values and lifespans, limited financing options.
- **Social**: Consumer resistance, range anxiety, cultural attachment to ICEVs

- **Industrial**: Limited domestic EV production, skill shortages, inertia/resistance from legacy auto and oil sectors.
- **Environmental**: Battery production/disposal concerns; risk of grid "recarbonisation" if not carefully managed.

## Discussion

The study's integration of scenario planning, structural analysis, and forecasting offers:

- A holistic view of decarbonisation pathways tailored to national realities — a notable advance over prior single-method or "global generic" studies.
- Improved capacity to map variable interdependencies (e.g., how charging infrastructure investment interacts with consumer adoption and industrial policy).
- Aggressive, coordinated policy is important but must be adapted to Brazil's specific strengths — particularly, the existing ethanol and flex-fuel vehicle infrastructure.
- Policies must address not just vehicle incentives and infrastructure but workforce development, manufacturing capacity, and social acceptance.
- "Balanced transition" strategies (mixing EVs and biofuels) are potentially optimal for Brazil, especially in the short to medium term.

Limitations of this study include:

- Exclusion of heavy-duty vehicles and other transport sectors.
- Economic modelling (esp. full lifecycle/transition costs) could be deepened.

- This study does not consider possible disruptive technology breakthroughs not currently visible (“unknown unknowns”).
- Land use impacts and indirect emissions from ethanol production merit further analysis.

## Conclusion

- Substantial GHG emission reductions from Brazil’s LDV sector (7–26% by 2050) are possible but not automatic; they require ambitious and integrated policies.
- Strategic priorities include clear ICEV phase-out timelines, expansion of charging infrastructure (including outside major cities), grid modernization, sustained emphasis on “sustainable ethanol,” public education, and domestic value chain development for EVs and batteries.
- The transition’s feasibility is higher if leveraged alongside existing flex-fuel capacity; full electrification may be gradual, allowing infrastructure, cultural and economic factors to align.
- Future research should (a) integrate heavy-duty vehicle/other modal analysis, (b) deepen economic cost-benefit assessment, and (c) track urban planning and smart mobility impacts on adoption.
- The integrative scenario-forecasting framework can serve as a model for other countries with dual clean energy–biofuel profiles.

## Resumo

Herzog, Heinrich Gustave; Calili, Rodrigo Flora (Orientador); Almeida, Maria Fatima Ludovico de (Co-orientadora). **Avaliando o Impacto da Eletrificação na descarbonização do Segmento de Transporte Rodoviário no Brasil no Horizonte de 2050.** Rio de Janeiro, 2024. 156 p. Dissertação de Mestrado – Departamento de Engenharia Civil e Ambiental, Pontifícia Universidade Católica do Rio de Janeiro.

A eletrificação da frota de veículos leves é uma estratégia essencial para mitigar as emissões de gases de efeito estufa no segmento de transporte rodoviário. Esta dissertação avalia o impacto potencial da eletrificação da frota de veículos leves no Brasil até 2050, empregando uma metodologia prospectiva para construir cenários alternativos de descarbonização, que combina abordagens de prospecção e previsão. A pesquisa tem dois principais objetivos: (i) estimar a potencial redução das emissões de gases de efeito estufa com a eletrificação da frota até 2050 no Brasil, em diferentes cenários de descarbonização, e (ii) analisar as barreiras à eletrificação da frota de veículos leves e respectivas implicações para os principais *stakeholders*. Os resultados indicam que a eletrificação tem potencial significativo para aumentar a descarbonização da frota de veículos leves do Brasil, com reduções estimadas de emissões de gases de efeito estufa variando de 7,0% no cenário menos ambicioso a 25,7% no cenário mais ambicioso até 2050. Este estudo conclui que a descarbonização da frota de veículos leves do Brasil exigirá uma abordagem coordenada e multiatores para superar esses desafios e implementar estratégias eficazes. Também recomenda pesquisas futuras e desenvolvimento de políticas voltadas para alcançar reduções significativas de emissões por meio da eletrificação da frota até 2050.



### Palavras-chave

Transporte rodoviário; eletrificação; descarbonização; redução da emissão de gases de efeito estufa; modelagem de cenários prospectivos; análise morfológica; Brasil.

# Summary

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# List of Abbreviations

A – Ampere
ABVE – Associação Brasileira de Veículos Elétricos
AC – Alternating Current
ANEEL – Agência Nacional de Energia Elétrica
ANFAVEA – Associação Nacional dos Fabricantes de Veículos Automotores
BAU – Business-as-usual
BEV – Battery Electric Vehicle
Co – Cobalt
DC – Direct Current
DN – Distribution Network
EPE – Empresa de Pesquisa Energética
EV – Electric Vehicle
FCEV – Fuel Cell Electric Vehicle
Fe – Iron
GDP – Gross Domestic Product
GHG – Greenhouse Gas
GMA – General Morphological Analysis
GVW – Gross Vehicle Weight
GWh – Gigawatt hour
HEV – Hybrid Electric Vehicle
HDV – Heavy-Duty Vehicle
IBGE – Instituto Brasileiro de Geografia e Estatística
ICCT – International Council on Clean Transportation
ICE – Internal Combustion Engine
IEA – International Energy Agency
IRENA – International Renewable Energy Agency
Km - Kilometre
kW – Kilowatt
kWh – Kilowatt hour
LCA – Lifecycle Assessment
Mbd – Millions of barrels per day
MDV – Medium-Duty Vehicle
MJ – Mega Joules
MME – Ministério de Minas e Energia
Mn – Manganese
MRL – Manufacturing Readiness Level
Na-ion – Sodium-ion
Ni – Nickel
LCV – Light Commercial Vehicle
LDV – Light-Duty Vehicle
LFP – Lithium iron phosphate
Li - Lithium
Li-ion – Lithium-ion
PBE – Programa Brasileiro de Etiquetagem
PEV – Plug-in Electric Vehicle
PHEV – Plug-in Hybrid Electric Vehicle
PNE – Plano Nacional Energético

PNEf – Plano Nacional de Eficiência Energética
PNME – Plataforma Nacional da Mobilidade Elétrica
R&D – Research and Development
SUV – Sport Utility Vehicle
TRL – Technology Readiness Level
T&D – Transmission and Distribution
US – United States
USD – United States Dollar
WtW – Well-to-wheel
WPT – Wireless Power Transfer
V – Volt
V2B – Vehicle-to-Building
V2G – Vehicle-to-Grid

# 1
# Introduction

The transportation sector is responsible for roughly 1/6 of total global emissions (IEA, 2023a). A transition towards less carbon intensive travel modes and more energy efficient options will be needed in the next couple of decades if countries are to fulfil their pledges to limit global warming. Besides shifts towards active and public transport, electrification is also essential to limit emissions.

Road transport is responsible for 45% of oil demand globally and 73% of emissions in the transportation sector, having the greatest potential for emissions reduction. In 2023, the share of electric vehicles (EVs) rose to 18% of global vehicle sales. Since the use of electricity in transportation is more efficient than fossil fuels, smart electrification will reduce total energy demand for the same amount of energy services (IRENA, 2022). Still, 91% of the transportation sector's energy consumption comes from fossil fuels and although progress has been made on biofuels in the last few decades, Brazil being a big contributor, greenhouse gas (GHG) emissions by biofuels have large variations depending on the technology and on a lifecycle basis (IEA, 2023a).

The electrification of the Light-Duty Vehicle (LDV) fleet has emerged as a key strategy for mitigating Greenhouse Gas (GHG) emissions from the road transportation segment. As global efforts to combat climate change intensify, the transition to electric vehicles (EVs) in the LDV sector presents a significant opportunity for reducing carbon emissions and improving air quality in urban areas (IEA, 2023a). This dissertation aims to assess the potential impact of electrifying Brazil's LDV fleet by 2050, employing a prospective methodology to build alternative decarbonisation scenarios that combine foresight and forecasting approaches.

The LDV category, comprising passenger cars and Light Commercial Vehicles (LCVs), is a major contributor to global $CO_2$ emissions. In 2022, LDVs accounted for approximately 15% of global energy-related $CO_2$ emissions (IEA, 2023a). The electrification of this sector offers significant potential for emissions reduction, particularly when coupled with the decarbonization of electricity grids (Knobloch et al., 2020).

Brazil presents a unique case for LDV fleet electrification due to its distinctive energy matrix and established ethanol industry. With 88% of its electricity generation coming from renewable sources (EPE, 2023), Brazil has a significant advantage in terms of the potential environmental benefits of EV adoption. However, the country's strong ethanol industry and the prevalence of flex-fuel vehicles introduce additional factors to consider in the transition to electrification (Costa et al., 2021).

This research has two main objectives: (i) to estimate the potential reduction in GHG emissions from fleet electrification by 2050 in Brazil across different decarbonisation scenarios, and (ii) to analyse the barriers to implementation in each scenario, along with their implications for key stakeholders. By exploring various scenarios, this study aims to provide valuable insights into the potential pathways for decarbonising Brazil's LDV fleet and the challenges that need to be addressed to achieve significant emissions reductions.

Recent studies have highlighted the importance of considering country-specific contexts when assessing the potential for the LDV fleet electrification. Factors such as electricity grid carbon intensity, policy support, charging infrastructure development, and consumer preferences all play crucial roles in determining the success of EV adoption and its impact on emissions reduction (Wappelhorst, 2021; Broadbent et al., 2022).

This dissertation aims to evaluate the extent to which electrification can enhance the decarbonisation of the LDV fleet in Brazil by exploring five different scenarios in the 2050 horizon. The study contributes to the existing body of knowledge by providing a comprehensive analysis of the Brazilian context, considering the unique interplay between electrification and the country's established biofuel industry. By employing a mixed-methods approach that combines prospective scenario planning with forecasting techniques, this study offers a nuanced understanding of the potential trajectories for LDV fleet electrification in Brazil and its implications for GHG emissions reduction.

## 1.1. Definition of the research problem

Considering that:

- There are many possible paths to decarbonisation, their long-term impact should be assessed so that decision makers can have a clearer picture of the most effective ones;
- Road transport is responsible for 45% of oil demand globally and 73% of emissions in the transportation sector, having the greatest potential for emissions reduction;
- Electricity generation in Brazil is clean, when compared to developed economies, with 88% being renewable;
- No previous studies were identified during the literature review that used prospective scenario planning combined with forecasting techniques to assess the impacts of electrification on decarbonisation scenarios of the LDV fleet in long-term horizons;

the following guiding questions were defined for this research:

- To what extent can electrification enhance the decarbonisation of the LDV fleet in Brazil considering the 2050 time-horizon?
- What barriers need to be overcome for the successful electrification of the LDV fleet in Brazil by 2050?

## 1.2. General and specific objectives

The general objective of this dissertation is two-fold: (i) to estimate the potential reduction in GHG emissions from fleet electrification by 2050 across different decarbonisation scenarios, and (ii) to analyse the barriers to implementation in each scenario, along with their implications for key stakeholders.

This general objective can be divided into six specific objectives:

- Discuss the relevance of prospective scenario modelling integrated with forecasting techniques for assessing the impact of electrification on the decarbonisation of different sectors in long-term horizons;
- Describe the conceptual framework of prospective scenario modelling, combining foresight and forecast approaches, to assess the impacts of

electrification on the decarbonisation of different sectors in long-term horizons;

- Map the methods and tools adopted in empirical studies on the impact assessment of electrification on the decarbonisation of the transport sector in general, and of LDV fleet in particular, to identify the research gaps addressed in this dissertation;
- Propose a conceptual model to build prospective scenarios for assessing the impact of electrification on the decarbonisation of the LDV fleet in Brazil by 2050;
- Estimate the potential for reducing GHG emissions resulting from the electrification of the LDV fleet in different decarbonisation scenarios in Brazil by 2050;
- Analyse barriers that should be overcome to implement electrification in the LDV fleet in Brazil and implications for policymakers, researchers, and transport sector stakeholders.

## 1.3 Methodology

The research can be classified as descriptive, methodological, and applied, based on the taxonomy proposed by Vergara (2015; 2016). The methodology employed throughout the study is structured into three distinct phases: (i) exploratory and descriptive; (ii) applied research, centred on a preliminary academic experiment; and (iii) conclusive.

The following subsections provide a detailed description of each of these phases.

### 1.3.1. Exploratory and descriptive phase

This phase involved a comprehensive literature review of key reference documents and scientific articles published between 2000 and 2024. Systematic searches were conducted across leading scientific databases, namely Scopus, Web of Science, Science Direct, and Compendex databases, as well as institutional websites, including those of Empresa de Pesquisa Energética (EPE) (Brazil); Fraunhofer Institut (Germany); International Council on Clean Transportation

(ICCT); International Energy Agency (IEA), and International Renewable Energy Agency (IRENA).

The scope of the literature review was further expanded through a backward search, whereby references cited in the initially selected articles were analyzed to identify foundational and influential works, including grey literature, to explore the central theme of the research, that is, the potential impact of electrification on decarbonising the LDV fleet. From this review, it was possible to identify the research gaps addressed in this dissertation and build a conceptual framework to generate distinct prospective decarbonisation scenarios, aiming to answer the two guiding questions set out in section 1.1.

### 1.3.2. Applied research phase

In this phase, a mixed methodological approach was employed for the construction of alternative prospective scenarios, which combines two scenario planning methodologies (Schwartz, 1998; Godet, 2000) with forecasting techniques (Hair et al., 2019). This approach consists of eight steps described below:

- Definition of the guiding questions for constructing scenarios and time horizon to be considered (Schwartz, 1998);
- Definition and classification of key variables, through the use of the structural analysis technique (Godet, 2000);
- Identification of the main stakeholders and influencers of the scenarios (Godet, 2000);
- Characterization of the current situation (2024) and identification of future determinants in the considered horizon (Godet, 2000);
- Construction of prospective scenarios, using the morphological analysis (Zwicky, 1969). This step also includes the verification of the consistency and plausibility of the configurations and the selection of the most probable scenarios;
- Estimating the size of the LDV fleet and the potential reduction of GHG emissions (Hair et al., 2019);
- Description of the prospective scenarios, including: philosophy, trajectories in the periods 2025-2030; 2031-2040, and 2041-2050 (Godet, 2000);

- Analysis of barriers to implementing electrification of LDV fleet in Brazil by 2050 and the strategic implications for overcoming them within this time horizon (Godet, 2000).

### 1.3.3. Conclusive phase

In the conclusive phase, conclusions were drawn in relation to the objectives set out in section 1.2. A set of recommendations was formulated for stakeholders interested in applying the model presented in this study, to estimate the potential GHG emissions reduction in the road transport sector resulting from electrification.

## 1.4. Dissertation structure

The dissertation is structured in five chapters, including this introduction. Chapter 2 presents the results of a comprehensive literature review and document analysis of transport electrification technologies, their potentials, and limitations, covering key aspects such as EV propulsion systems, energy storage, charging systems, and infrastructure. This chapter includes a summary table of 25 selected studies on transport electrification, decarbonisation, and adoption barriers, highlighting their relevance to this research.

Chapter 3 proposes a conceptual framework for prospective scenario planning modelling, designed to assess the potential impacts of electrification on the decarbonisation of Brazil's light vehicle fleet. A mixed methodological approach is employed for the construction of alternative prospective scenarios, which combined two scenario planning methodologies (Schwartz, 1998; Godet, 2000) with forecasting techniques (Hair et al., 2019).

Chapter 4 presents five decarbonisation scenarios for Brazil's light vehicle fleet through 2050, elucidating the complex interplay among policy frameworks, technological advancements, and societal factors that may influence the trajectory of fleet electrification during this period. These scenarios are constructed to encompass near-term (2025–2030), medium-term (2031-2040), and long-term (2041–2050) trajectories, offering a comprehensive analysis of how initial policy decisions and interventions could significantly shape the decarbonisation landscape of the LDV fleet by mid-century. The five scenarios span a spectrum from minimal to extensive electrification and decarbonisation, providing a prospective view of the potential evolution of the Brazilian LDV fleet composition and its consequent impact on GHG emissions. This chapter includes a detailed analysis, including strategic implications of 16 barriers to the implementation of electrification of the LDV fleet in Brazil by 2050.

In Chapter 5, the research conclusions are presented and recommendations for future studies are addressed, such as in-depth analysis of the relevant aspects that emerged from this dissertation.

# 2
# Road transport electrification and decarbonisation

This chapter presents the results of a comprehensive literature review and document analysis of transport electrification technologies, their potentials, and limitations, covering key aspects such as EV propulsion systems, energy storage, charging systems, and infrastructure. It includes a summary table of 25 selected studies on transport electrification, decarbonisation, and adoption barriers, highlighting their relevance to this research.

## 2.1.
## Electric vehicles

An EV propulsion system converts electrical power into mechanical power, and may consist of many different energy storage devices, including batteries, fuel cells, and supercapacitors. Electric motors tend to be lighter and more efficient than internal combustion engines (ICEs) because of the excessive heat loss and cooling systems of ICEs (Emadi et al., 2005).

Vehicles powered by electric motors also require less maintenance and emit fewer local pollutants, since there are no direct emissions. The propulsion system in an EV can be a complex assembly that involves mechanical, electrical, electrochemical, magnetic, thermal, and control aspects (Emadi et al. 2005). The fuel tank, which stores energy in an ICE vehicle, is replaced by a battery bank in an EV. A power controller is used to control the battery voltage and the power supply to the motor. Auxiliary devices are typically powered by separate 12 V batteries. Figure 2.1 illustrates a typical BEV propulsion system.

Electric motors have always been used in industrial applications, but normally under constant speeds for long periods of time. In vehicle applications, motors need to be able to constantly accelerate and decelerate, stop and start frequently, and operate in environments that are far from ideal.

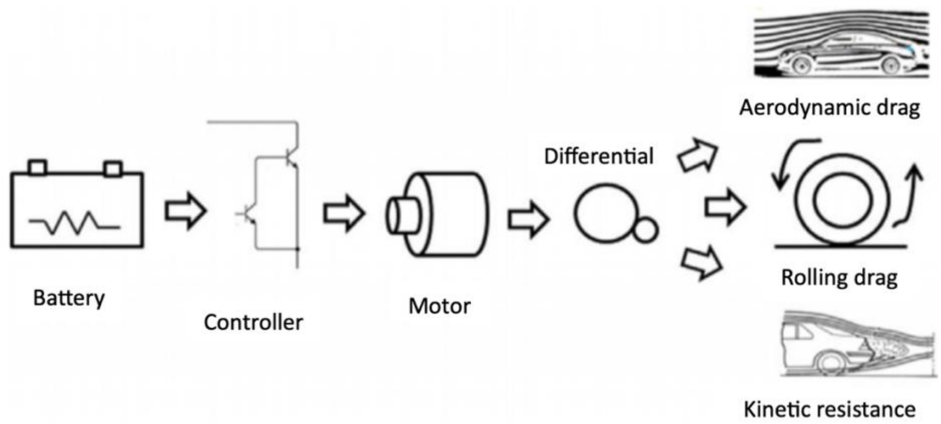


Figure 2.1 – BEV propulsion system
Source: Adapted from Kumar and Revankar (2017).

There are generally three categories of EVs (Miele et al., 2020), based on the energy source and reliance on auxiliary engines.

- Hybrid Electric Vehicle (HEV) – a vehicle with two or more energy sources, at least one of them being electric. Most HEVs work as an ICE vehicle with one or more battery powered auxiliary engines. The battery is recharged by regenerative braking in most HEVs, but some can also be recharged through the ICE.
- Plug-in Electric Vehicle (PEV) – a battery powered vehicle that can be plugged to a charging station for recharge. These include Plug-in Hybrid Electric Vehicles and Battery Electric Vehicles:
    - Plug-in Hybrid Electric Vehicle (PHEV) – A battery-powered vehicle with an auxiliary ICE. These vehicles usually have a battery range of 20 km to 50 km.
    - Battery Electric Vehicle (BEV) – a vehicle 100% powered by batteries, with no auxiliary ICEs.
- Fuel Cell Electric Vehicle (FCEV) – an electric vehicle where the energy stored in the fuel, (typically hydrogen stored in a high-pressure tank) is converted through fuel cells.

## 2.2.
## Energy storage

Batteries are what power EVs, and progress in their development is one of the main reasons why it is now possible for the transportation sector to transition away from fossil fuels. Most EV models use Lithium-ion (Li-ion) batteries, due to their high energy density and load capabilities. Further progress has been made in the last few years in battery technology, with a reduction in costs and improvements in energy density and safety. According to Fraunhofer (2022), battery production not only for EVs but also for energy storage in residential and industrial applications is expected to grow significantly with electrification. New chemistries are being researched to improve performance and reduce costs. Systems based on nickel (Ni), iron (Fe), manganese (Mn), and cobalt-free systems are being developed for cathodes. Ni and cobalt (Co) are scarcer and more expensive minerals, although batteries based on these appear to perform better in high-energy applications. On the anode side, graphite and graphite-silicon are established composites, but silicon-based systems also appear to show promise (Fraunhofer, 2022). Table 2.1 provides an overview of the available energy storage technologies.

Table 2.1 – Energy storage technologies

| Technology | Characteristics | Potentials | Limitations |
|---|---|---|---|
| Lead-acid | Lead oxide acts as the positive active material and soft lead as the negative active material, which creates a current between the two terminals. Dilute sulphuric acid is typically used as the electrolyte in lead acid batteries. | Lead-acid batteries are widely used in industrial applications, including in ICE vehicles for auxiliary power supply such as ignition and lighting. They deliver a short burst of high power to start the engine. Deep cycle lead-acid batteries can also deliver a lower, steady level of power for a longer time (Battery Council International, 2024). | Lead-acid batteries have low specific energy; slow charge; limited life cycle; and are not environmentally friendly (Battery University, 2010c) |
| Li-ion | In the most common Li-ion batteries used in EVs, positively charged Lithium (Li) ions move between the anode and the cathode in an electrolyte (Kumar and Revankar, 2017). Graphite or silicon (Si) anodes are typically used with an organic solvent liquid electrolyte. Oxidized Co is used for the positive electrode and carbon material for the negative electrode. During charging, the ions flow from the cathode to the anode, and during discharge, from the anode to the cathode. | Li-ion batteries have high specific energy and load capabilities; high capacity; low internal resistance; long life-cycle and shelf life; low maintenance; relatively short charge times; and low self-discharge. These traits turned these batteries into the preferred option for EV manufacturers as they are able to provide high energy density and fast charge in a light package. | They present a fire risk; require a protection circuit to prevent thermal runaway when stressed; they can degrade in high temperatures or when stored in high voltages; they lose capacity and charging speed at below freezing conditions; and have special requirements for shipping in large quantities (Battery University, 2010a), due to safety concerns. |
| LFP | LFP or $LiFePO_4$ is a stable three-dimensional phospho-olivine, which occurs as the natural mineral triphylite. It delivers 3.3–3.6 V and more than 90% of its theoretical capacity of 168 Ah $kg^{-1}$ (Garche and Brandt, 2018). | LFP batteries have high power density, longer lifespans, lower costs, have better thermal and chemical stability and are safer, compared to Li-ion. They can withstand high temperatures, are | LFP batteries have much lower energy density than Li-ion batteries (Kumar and Revankar, 2017). |

| | | | |
|---|---|---|---|
| | | incombustible and relatively stable in overcharge and short circuit conditions (Garche and Brandt, 2018). | |
| Na-ion | Na-ion, or sodium-ion, batteries store energy using sodium ions. Anodes typically use carbon-based materials like hard carbon or graphite. Cathodes often employ transition metal oxides such as sodium cobalt oxide or sodium iron phosphate. The anode and cathode are separated by an electrolyte, which can be liquid or solid. | Na-ion batteries are composed of lower cost materials than Li-ion and completely avoid the need for critical minerals in manufacturing (IEA, 2023b). | Na-ion batteries have low energy density, lower than any Li-ion battery on the market (IEA, 2023a). Therefore, less demanding applications such as micro mobility and stationary storage are being touted as more realistic targets for Na-ion batteries. |
| Fuel cells | Inside the fuel cell, hydrogen molecules are split into protons and electrons at the anode, with the aid of a catalyst. The protons pass through an electrolyte membrane to the cathode, while the electrons travel through an external circuit, creating an electric current. At the cathode, oxygen from the air combines with the protons and electrons to form water and heat (Office of Energy Efficiency and Renewable Energy, 2024). | Today, the most commonly used fuel is hydrogen, due to its high energy density and non-polluting nature, as the only by-product is water and heat. FCEV technology shows more potential in Heavy-Duty Vehicles (HDVs) due to the high battery prices for these vehicles. | Recent studies have suggested FCEVs are not as energy efficient as BEVs, demanding higher primary energy and having a higher total cost of ownership. Emissions from hydrogen production can vary widely depending on the source. It is still in an early stage of development and commercialization, and would need more investments in refuelling infrastructure (Plötz, 2022). |

## 2.3. Charging systems

EV charging systems are divided into three levels depending mainly on the power output. Level 1 (L1) chargers are included for every EV and are compatible with regular household outlets. These are the cheapest and slowest chargers in the market. Level 2 (L2) chargers are commonly used in public and residential locations such as parking garages in offices, residential buildings, businesses, and schools. Level 3 (L3) chargers, also known as DC Rapid Chargers, are the fastest chargers and are capable of charging a battery to 80% in as little as 20 min. Above 80% charge, all charging is performed in the slow mode (Mastoi et al., 2022) to avoid damaging the battery. Owing to their charging speed, they provide the closest experience to a refuelling station, to which most customers are accustomed. The drawback is the cost of these chargers, because they are significantly more expensive than the alternatives. L3 chargers also have a larger impact on Distribution Networks (DNs) than other chargers, potentially demanding upgrades to the grid. They are commonly installed at rest stops, shopping malls, and government buildings. Table 2.2 summarises some charger-level specifications.

Table 2.2 – Charger level specifications

| | Level 1 (L1) | Level 2 (L2) | Level 3 (L3) |
|---|---|---|---|
| **Current** | AC | AC | DC |
| **Voltage** | 120-220 V | 220-400 V | 200-800 V |
| **Amps** | Max. 16 A | 12-80 A | 80-200 A |
| **Load** | Max. 2.4 kW | 2.5-19.2 kW | 36-240 kW |
| **Charge Time** | 5-8 km/h* | 16-32 km/h* | 80% charge in 20-40 mins. |

*Km of range added per hour charged
Source: Mastoi et al. (2022).

The most common way to charge an EV is by plugging it into a charger; however, there are a few other ways to recharge it. These methods include inductive charging, pantograph charging, and battery swapping. Inductive charging, also known as Wireless Power Transfer (WPT), consists of a two-coil system based on electromagnetic induction, with a transmitter coil on the road surface and a receiving coil in the vehicle. In addition to the potential to be conveniently placed under parking spots, they can also be installed in places where vehicles make frequent stops on the road, such as traffic lights.

Pantograph charging, as the name suggests, consists of a pantograph, typically mounted on a charging station or overhead structure that extends towards a receptor on the EV, enabling rapid power transfer. This system is commonly used for buses, trucks, and other large vehicles where high-power charging is required. Because charging can be performed frequently, this system demands less range from the batteries, reducing their cost. However, infrastructure costs tend to increase.

Battery swapping is a method in which an EV battery is replaced and recharged outside the vehicle. This method typically involves renting batteries or having a membership in a battery swap station owner. This experience is similar to that of a refuelling station, and it allows batteries to be charged slowly, giving them longer life cycles (Ahmad et al., 2017).

## 2.4. Charging infrastructure

When located efficiently, charging stations are essential to ensure access to cheap and clean energy from renewable sources and to facilitate quicker adoption of EVs (Sathaye and Kelley, 2013). They can also reduce range anxiety, that is, the worry that an EV user will run out of energy before reaching their destination. For drivers who can afford to install equipment in their garages, most EV charging is performed at home. These users tend to be single-family homeowners, who can install charging stations more easily. For them, public charging would be useful only for long trips and other exceptional circumstances. For users who drive long distances daily or have difficulty installing charging equipment at home, public charging becomes a necessity. For this reason, more vertical and dense urban centres tend to have more demand for public charging.

Most investments in public chargers have been towards the deployment of DC Rapid Chargers. Initially, it was anticipated that fast-charging stations would be more useful on highway exits and rest stops, where users would travel long distances and have little time to stop. However, they have also proven popular in urban centres, where there are few options for home charging or at working hours. In studies presented by the London Mayor’s Electric Vehicle Infrastructure Taskforce, most fleet vehicles tend to be operated by companies that have depots with their own charging systems and would need public charging only occasionally. However, commercial vehicles operated by small businesses would benefit from more public charging, since they are more sensitive to the high prices of DC Rapid Chargers. Ride-hailing and taxi drivers also tend to benefit from public L3 chargers, as they drive long distances daily, without much time for long pauses.

The control and communication infrastructure for EV charging is important for integration into the grid because the uncoordinated charging of EVs may cause problems for DN operators. Charging scheduling solutions consider EV arrival and departure times in charging stations to optimize performance. When charging is performed in an uncoordinated manner during peak times, it may lead to power losses, overloading of the transformers, and reduced DN reliability (Masoum et al. 2012). Currently, most charging systems can be manually coordinated by the user. It can start immediately as soon as the vehicle is plugged into the power source or it can be scheduled for a later time.

Most private users tend to plug in their vehicles after arriving home from work at 17:00 or 18:00, which, in many cases, is peak demand time. Users can avoid peak demand times by scheduling charging times for off-peak hours. If there are higher energy rates for peak hours, they can also be avoided through scheduling.

Many electric utility companies offer time-of-use tariffs to consumers, or “white tariffs,” as they are called in Brazil. Generally, they charge higher tariffs during peak demand hours, such as 18:00 to 21:00 or 17:00 to 20:00. The lowest demand is usually found at night, from 22:00 to 6:00. Demand response regulation is a significant step towards a more efficient distribution system.

Higher tariffs in peak demand times come with the assumption that the supply or power generation in this case is constant. With the rise in solar generation, the supply tends to increase during the day, which makes a better case for daytime charging of EVs. This is the case not only from an economic perspective but also in terms of emissions, since there would be more supply from renewables at the time.

With smart charging, scheduling can be automated and optimized. By identifying the times of high and low demand and EV charging points, vehicles can be charged only when the loads are low. This type of charging can aid in the reactive power supply, peak demand shaving, and harmonic reduction (Mastoi et al., 2022). This technology can avoid transformer overloads and voltage and current deviations, and reduce electricity costs (Fairley, 2010). Smart charging is even more relevant in a grid composed of renewables considering the intermittent nature of these energy sources.

Effective communication between EVs and the grid is crucial in this case. Digitalisation is a cornerstone in the transition to electrification with renewables, according to IRENA (2022a). The integration of digital technologies enables the real-time monitoring and control of energy systems, leading to enhanced efficiency, reliability, and flexibility of the power grid.

Advanced metering infrastructure, smart sensors, and automated control systems allow for precise balancing of supply and demand, optimization of energy generation, and effective integration of distributed energy resources. This real-time capability is crucial for managing the intermittent nature of renewable energy sources, ensuring their optimal use, while minimizing waste and improving grid stability.

Digitalization also supports the flexibility and adaptability of energy systems necessary to handle the variable output from renewable sources such as solar and wind. Using data analytics and artificial intelligence, energy providers can implement predictive maintenance, optimize grid operations, and forecast energy production and consumption patterns. This predictive ability helps manage the variability of renewables by enabling proactive adjustments and the efficient coordination of energy resources. Additionally, digitalisation facilitates demand response strategies, allowing consumers to adjust their energy usage based on supply conditions, thus enhancing the overall grid efficiency and reliability (IRENA, 2022a). Furthermore, digitalisation empowers consumers by transforming them into active participants in the energy ecosystem.

Technologies, such as smart meters and home energy management systems, provide real-time information about energy consumption, enabling consumers to make informed decisions and participate in energy-saving programs. This level of consumer engagement is critical for the success of smart electrification as it encourages energy efficiency and demand-side management. Moreover, digital platforms support new business models and services, such as peer-to-peer energy trading and virtual power plants, which leverage distributed energy resources to enhance the resilience and sustainability of energy systems. Overall, digitalisation not only optimizes the technical aspects of energy distribution, but also fosters a more interactive and participatory energy landscape (IRENA 2022a).

The introduction of EV charging in power grids, coupled with the advent of smart meters in buildings and industry, is bringing significant changes to the operation of DNs. Traditionally, DNs have a unidirectional flow of energy from large producers to consumers. Small renewable sources and energy storage systems, such as EV batteries, have introduced the possibility of bidirectional flow. Smart grids enable two-way communication between consumers and distributors by integrating smart meters and devices into a network, allowing remote monitoring, analysis, and management of the entire system.

Data sharing is essential in smart grids, which require an extensive communication network, with many different types of equipment being able to send, receive, store, and analyze data. Control over access to these data becomes crucial to its function (Rogozinski and Calili, 2021). Without smart grids, the increased complexity introduced by renewable energy sources and energy storage systems can have a negative impact on DNs.

EVs, acting as both distributed energy storage devices and dynamic loads, introduce nonlinear load characteristics and power quality deterioration into the grid, exacerbated by the uncertainties surrounding their charging times, power ratings, and connection locations. Therefore, the large-scale connection of EVs to smart grids raises substantial concerns regarding the power system stability.

Voltage instability emerges from EVs' power demand, which requires adequate system planning and EV operations.

Optimal placement, quantity, and power rating of EV charging stations are important for minimizing voltage stability issues and ensuring compatibility with the network structure (Dharmakeerthi et al., 2014).

Considering the challenges of growing electrification, operators have two options: enlarging the electricity network, which is costly and time-consuming, or implementing energy-management strategies. Smart grids leverage EVs as alternative energy sources, like wind and solar power, allowing the control of energy usage based on the production levels of other sources. EVs can store surplus energy from renewables, thus supporting the grid during periods of increased electrical demand. Optimized scheduling techniques improve the operational efficiency of clean energy sources, maximize the usage of clean energy, and reduce reliance on conventional fuels (Hu et al., 2014).

Moreover, EV-smart grid integration facilitates reactive power compensation, improves the system power factor, enhances system capacity, and reduces network losses, thus optimizing energy usage and reducing the costs associated with new installations (Inci et al., 2024). Integration with EVs not only improves energy efficiency, but also enhances consumer access to real-time power consumption data, empowering users to make informed decisions about their energy usage.

According to review article on EV integration in smart grids, authored by Inci et al. (2024), the potential benefits of integration are significant and encompass improved grid stability, increased renewable energy integration, and reduced environmental impact. However, realizing these benefits will require addressing infrastructure, data management, policy, and regulatory challenges. Effective policy and regulation are critical to enable integration, whereas ensuring data privacy and security is crucial for system operation.

Distribution planning and optimization of charging station deployment are important areas that require attention. Collaboration among stakeholders, including utilities, regulators, policymakers, and technology providers, is essential for developing effective strategies and navigating EV integration complexities.

According to Rogozinski and Calili (2021), the main issues that must be overcome in the Brazilian network include voltage fluctuations, high demand during peak hours, power losses, and technical and non-technical losses such as fraud and default. The introduction of smart-grid elements can contribute to solving these issues. The installation of smart meters can reduce energy theft and defaults, and the installation of switches and remote-controlled circuit breakers can reduce interruptions in large load blocks. The introduction of variable tariffs for big consumers, also enables a reduction in demand during peak hours. A decentralized network with greater consumer input and service options is still being introduced into the Brazilian market.

## 2.5. Current situation of transport electrification in the world

The global EV stock has surpassed 42 million in 2023 and total sales have reached 14 million, according to IEA's numbers. Total electricity demand from EVs reached 124,300 GWh in the same year. The following sections present the current situation of transport electrification in the world. Table 2.3 presents the different vehicle categories based on Gross Vehicle Weight (GVW) and usage.

Table 2.3 – Vehicle categories

| | |
|---|---|
| Light-Duty Vehicle | Vehicles weighing up to 3.5 tons GVW* |
| Light Commercial Vehicle | Commercial vehicles weighing up to 3.5 tons GVW* |
| Medium-Duty Vehicle | Between 3.5 and 15 tons GVW* |
| Heavy-Duty Vehicle | Vehicles exceeding 15 tons GVW* |
| Bus | Passenger carrying Medium to Heavy-Duty Vehicles |

Note: *As defined by the IEA.

### 2.5.1. Light-duty vehicles (LDVs)

The total number of electric LDVs on the road globally reached 40 million in 2023 and sales grew by 35% compared to 2022 (IEA, 2024). At the same time, ICE sales have been dropping, with a 3% drop in 2022 and a 2% cumulative drop from 2016 to 2022. ICE vehicle registrations have peaked in 2017 at 85 million. A phase-out of purchase incentives for EVs in some of the major markets has led to a slowdown in sales in some regions and worries that the EV market is not mature enough to thrive without subsidies.

The growth in EV sales in the last few years has been spurred by wider model availability, increased range and improvements in performance (IEA, 2023b). Battery prices have dropped significantly in the past 15 years, with the average cost of a Li-ion battery dropping from USD 1,200 / kWh in 2010 to USD 132 / kWh in

2021, an 89% decrease (Houache et al., 2022). The increase in market share helps reduce the reliance that the traditional automakers have on ICE sales, making them direct more funding to Research and Development (R&D) and production of EVs. In the International Energy Agency's (IEA) Stated Policies (STEPS) scenario, the most conservative one in terms of the transition, EV sales are expected to represent 30% of vehicle sales by 2030. In the Net Zero (NZE) scenario, the more optimistic one, the 30% mark is expected to be reached by 2025, with 60% sales share by 2050.

China, Europe and the US are the three major markets for EVs. In these markets, fuel taxation, vehicle efficiency and emissions standards have helped spur a transition from ICE's. EV sales in emerging economies have been slow, especially in the ones with large car markets. High purchasing costs, a lack of access to reliable charging infrastructure, and maintenance services are cited by the IEA (2023b) as contributing factors to the low demand. A lack of options in terms of models is also an issue in emerging markets. Most EV model offerings are SUVs and luxury cars. These are expensive vehicles in markets that are highly sensitive to prices. However, more government incentives are being introduced and sales are showing signs of an upward trajectory. EV sales increased 50% outside of the three major markets in 2023 (IEA, 2024).

### 2.5.2. Light commercial vehicles (LCVs)

The sales of electric LCVs grew by 50% in 2023, compared to 2022, to reach a sales share of almost 5% (IEA, 2024). More than 98% of the sales were in the BEV category. Commercial vehicles are used more intensively than private cars, which leads to more substantial energy and emissions savings. These vehicles also tend to have shorter and more predictable routes, which makes it easier to plan for recharges. Another notable factor in the sales of LCVs is that commercial operators are more sensitive to economic fundamentals than private consumers. If EVs do not reduce operating costs for commercial fleet operators, which use the vehicles more intensively, it becomes difficult to justify a switch from ICEs. Low or zero emissions zones in cities also push the attractiveness of electric LCVs, since many of these vehicles operate in urban centres (IEA, 2023a). It is also important to note differences in LCV classification and characteristics between regions. In North

America, for instance, LCVs tend to be much larger and heavier than LDVs, while in India and China they are of similar or even smaller size.

### 2.5.3. Heavy-duty vehicles (HDVs)

Electrification of HDVs has been much slower than LDVs. Although they represent less than 5% of the global on-road vehicle fleet, they are responsible for more than a third of fuel consumption and almost three quarters of NOx emissions (MacDonnell and Kodish, 2023). In 2023, close to 54,000 electric trucks were sold, which represented 0.9% of total medium and heavy-duty truck sales worldwide. Electric buses (e-buses) fared better, with 66,000 sales and a 4.5% share of the bus market. Despite the low sales share of e-buses, a few countries saw more than 50% sales share in 2023, including Norway, Belgium, Switzerland and China. Electric truck sales increased three-fold in Europe and the US in 2023, though they still represent small sales share of 1.5% and 0.1%, respectively (IEA, 2024).

### 2.5.4 Charging infrastructure

The amount of public charging stations increased by 40% globally in 2023, with fast chargers outpacing slow ones, much of it helped by targeted policies in the major markets (IEA, 2024). The availability of charging infrastructure is essential for electrification growth. An increase in the number charging stations improves the convenience of owning EVs instead of ICE's, spurring growth in the EV market. This growth will, in turn, demand more charging stations. Their availability also helps combat range anxiety.

While most of the charging is done at home or at private locations, public charging is also important to provide the convenience needed to compete with ICE vehicles. Another factor is the difficulty found by many apartment dwellers in installing charging equipment. Most EV adopters tend to live in single-family homes, where it is simpler to install chargers.

According to the Electric Vehicle Council, 90% of EV owners in the US in 2021 had their own private garages to install equipment. For users who travel long distances daily and apartment dwellers, public charging would make it much more convenient to switch to an EV. Denser, more vertical city centres with more multifamily housing tend to have more demand for public charging (Hall and Lutsey, 2020).

## 2.6. Current situation of transport electrification in Brazil

The transport sector is the biggest energy consumer in Brazil, closely followed by industry, representing roughly one third of final energy consumption in the country. Historically, it has been dominated by road transport. Population growth and an increase in household income has led to rising demand for products and services in the last couple of decades, driving demand for more vehicles. Transportation policy in the country tends to focus on improvements in logistical systems, especially for freight transport (Eletrobras, 2019). More recent policies, however, have been focusing on modal integration and improvements in mobility.

Figures 2.2 and 2.3 show $CO_2$ emissions by fuel combustion and by sector in the world and in Brazil, respectively.

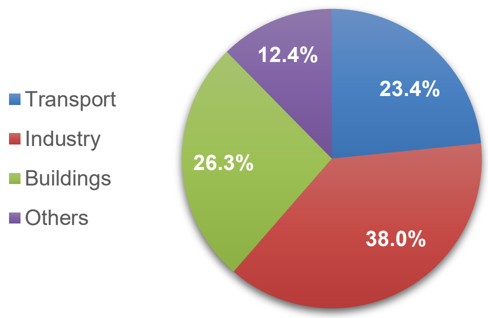


Figure 2.2 – Global carbon dioxide emissions by fuel combustion in 2021
Source: IEA (2023d).

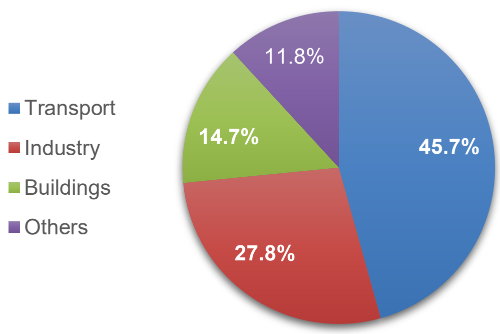


Figure 2.3 – Carbon dioxide emissions by fuel combustion in Brazil in 2021
Source: IEA (2023d).

It is evident that transport in Brazil represents almost 46% of emissions associated with fuel consumption, compared to 23.4% in the rest of the world. This provides a strong argument for making structural changes in this area, giving it greater efficiency and sustainability. The large share of transport emissions in Brazil is due, in big part, to the clean electricity mix in the country, with 88% of the sources being renewable, which leads to lower emissions from industry, buildings and others. Other contributing factors include the country's dependence on road transport and its large territory. Although ethanol, which is extensively used in Brazil, is a renewable source, it still leads to emissions in its lifecycle.

While the transition to electrification will take time in the country, natural gas and ethanol can also play an important role in the efforts to lower carbon emissions. Ethanol is a renewable energy source with a big presence in Brazil. Natural gas is also abundant, relatively cheap and with a growing piped distribution network, according to EPE (2023a). Flex fuel electric hybrids have been successful in Brazil as there is a robust refuelling infrastructure already in place.

In Brazil, 93,927 light-duty EVs (including HEVs) were sold in 2023, according to the Brazilian Association for the Electric Vehicle (ABVE), which is a 91% increase from the previous year. Of the total, 52,359 were PEVs. São Paulo was the state with the most sales with 35% of the market, followed by Rio de Janeiro and Minas Gerais, with 7.3% and 6.8%, respectively. For the first time in the country, plug-in EVs had a larger annual share of the EV market than hybrids, with 56% of sales. As of the end of August 2024, sales have already surpassed the previous year's number, with 94,616 EVs sold. Local incentives have contributed to adoption with tariff reductions in some states and municipalities. The increase in the number of EVs on the streets also boosted the deployment of the charging network, with a 28% increase in the number of charging stations in the country in 2023, for a total of 3,800.

Figure 2.4 shows the EV sales share evolution in Brazil since 2012, while Table 2.4 shows current Brazilian EV fleet data.

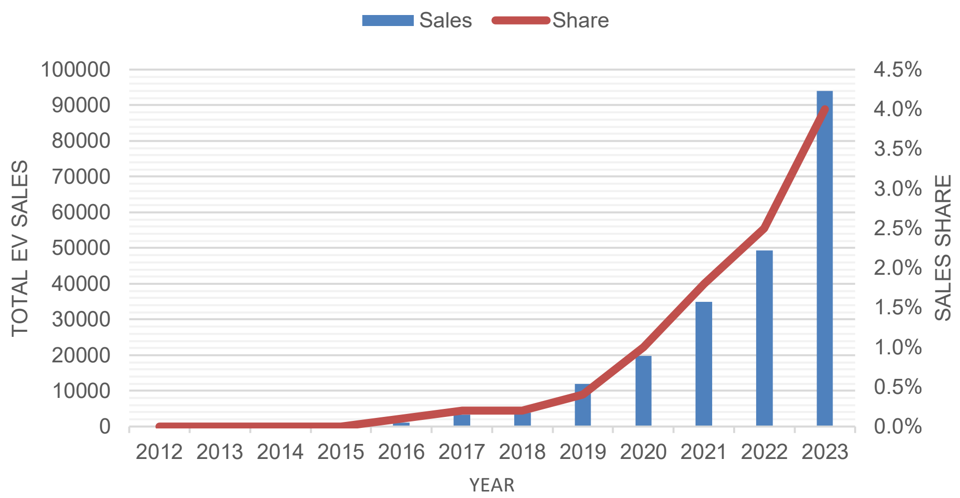


Figure 2.4 – EV sales per year in Brazil
Source: ABVE (2024b).

Table 2.4 – Brazilian EV numbers for 2023

| | LDV | LCV | Buses | M/HDV |
|---|---|---|---|---|
| BEV+PHEV stock | 92,000 | 1,500 | 1,200 | 1,900 |
| BEV+PHEV stock share | 0.2% | 0.02% | 0.2% | 0.08% |
| BEV+PHEV sales | 52,000 | 690 | 200 | 810 |
| Sales share | 3% | 0.2% | 0.5% | 0.6% |
| Sales Growth | 181% | 33% | -67% | 14% |
| Electricity demand (GWh) | 38,000 | | | |
| Oil displacement (Mbd) | 0.30 | | | |

Source: IEA Global EV Data Explorer.

Since 2000, energy demand in road transport has increased 3.1% per year on average, up to 2022. Energy demand from passenger road transport has increased 2.2% per year and freight road transport has increased by 4.8% per year. EPE (2023b) states that the increase in freight is largely due to record grain crop yields, as well as lower unemployment and increased consumer spending. Despite some progress in energy efficiency in the sector, diesel consumption has been increasing in the last 20 years, due to increasing truck usage. Freight activity saw a decline during the pandemic, but by 2022, it had already increased 23% compared to 2019, boosted by increased agricultural and industrial production. More demand for private vehicles since the Covid-19 pandemic has also contributed, with public transport ridership not having recovered to pre-pandemic levels. According to EPE (2023b) total mobility has not recovered either, due to hybrid work and unemployment.

Many automakers have been investing on EV manufacturing in the country and introducing new models to the market, with now more than fifty models for consumers to choose from. Much of this increase was due to the entrance of Chinese manufacturers in the market, with BYD, Chery and GWM, having big participation in EV sales. These electric models are still more expensive on average than their ICE equivalents and EPE (2023c) states that the degree of household debt incurred by vehicle purchases in Brazil is a barrier to EV adoption. However, the entrance of these manufacturers with cheaper models has helped lower EV prices from other manufacturers (PNME, 2023). BYD and GWM are also starting to invest in manufacturing for BEVs and hybrid ethanol electric models. BYD is also investing more than USD 600 million on its first vehicle plant outside Asia. The traditional automakers in Brazil have extensive knowledge of the market and vehicles that are especially adapted to it. While the Chinese manufacturers have great expertise in BEVs, there is very little knowledge in flex-fuel technology, for instance. Therefore, they also see the need to invest in R&D and engineering in Brazil.

There have been a few developments in terms of battery supply chain in the country, such as the first Li mines in Minas Gerais and the announcement of investments on battery manufacturing by Chinese companies, such as BYD. According to the National Electric Mobility Platform (PNME, 2023), the country needs to establish Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) targets for battery cell feedstocks. It is important to invest in processing facilities and develop the domestic supply chain. The country has one of the largest mining industries in the world and is an important producer of iron ore, bauxite and niobium; however, it exports much of the raw material, missing the opportunity to aggregate value to the product through processing and manufacturing capacity. Collaboration and integration between companies is key to develop supply chains, and it is not always a simple procedure, as there are many competing interests involved.

An examination of current policies related to road transport and energy efficiency in the country reveals that it has been only within the last 12 years that the electrification of transport has gained significant attention in policy discussions. The reduction of import tariffs for HEVs in 2015 played a crucial role in initiating the adoption of EVs nationwide. The 35% tariff was reduced to between 0 and 7%, depending on vehicle efficiency (PNME, 2023).

A Parliamentary Front for Electric Mobility was created in 2023 with the aim to identify barriers and opportunities for producers and consumers, as well as battery recycling. The Ministry of the Economy has also launched the Made in Brazil Integrado (MiBI) initiative, which focuses on Li-ion battery recycling.

Appendix 1 summarizes the Brazilian policies aimed at improving energy efficiency in transport over the last four decades.

## 2.7. Studies on transport electrification and decarbonisation

The bibliographic research was performed on three scientific databases, according to the search words presented in Table 2.5. An initial bibliographic search identified 58 studies related to electrification and decarbonisation for further analysis. A set of criteria was used to select 25 studies out of the 58. The criteria included: (i) use of scenario modelling, morphological analysis, or forecasting techniques; (ii) focus on the transportation sector; (iii) inclusion of the LDV fleet (either by itself or in context of the entire vehicle fleet); (iv) regional transport and energy context, with high renewable electricity generation and biofuel production; (v) analysis of barriers to transport electrification. Table 2.6 provides a summary of the 25 studies selected, detailing their objectives, geographical focus, and methodological approaches.

Table 2.5 - Search performed in scientific databases

| Database | Searches |
|---|---|
| Scopus | “scenario modelling” OR “morphological analysis” OR “impact assessment” OR “electrification” OR “decarbonisation” |
| | "methods" AND "tools" OR "electrification" OR "decarbonisation" OR "impact assessment" OR "transport sector" OR "transportation" |
| | "conceptual model" OR "prospective scenarios" OR "impact assessment" OR "electrification" OR "decarbonisation" OR "road transport" OR "Brazil" OR "2050" |
| | "potential" OR "greenhouse gas emissions" OR "electrification" OR "road transport" OR "scenarios" OR "Brazil" OR "2050" |
| | “barriers” OR “road transport” OR “electrification” OR “Brazil” |
| Web of Science | “scenario modelling” OR “morphological analysis” OR “impact assessment” OR “electrification” OR “decarbonisation” |
| | “methods” OR “electrification” OR “decarbonisation” OR “impact assessment” OR “transport sector” |
| | “prospective scenario” OR “electrification” OR “decarbonisation” OR “road transport” |
| | “potential” OR “greenhouse gas emissions” OR “electrification” OR “road transport” OR “scenarios” OR “Brazil” OR “2050” |
| | “barriers” OR “road transport” OR “electrification” OR “Brazil” |
| Compendex | “scenario modelling” OR “morphological analysis” OR “impact assessment” OR “electrification” OR “decarbonisation” |
| | "methods" and "tools" or "electrification" or "decarbonisation" or "impact assessment" or "transport sector" or "transportation" |
| | "conceptual model" OR "prospective scenarios" OR "impact assessment" OR "electrification" OR "decarbonisation" OR "road transport" OR "Brazil" OR "2050" |

| Database | Searches |
|---|---|
| | "potential" OR "greenhouse gas emissions" OR "electrification" OR "road transport" OR "scenarios" OR "Brazil" OR "2050" |

Of the 25 studies analysed, five addressed the transportation sector as a whole (Bramstoft and Skytte, 2018; MME/EPE, 2020; Gonçalves et al., 2022; IRENA, 2022; Raoofi et al., 2023), while one focused specifically on the offshore shipping sector (Spaniol and Hansen, 2021). The remaining studies concentrated on the road transport sector, including works by Silva (2011), van der Zwaan et al. (2013), Glensor and Rosa (2019), Helgeson and Peter (2019), Zhang and Fujimori (2020), Gerber Machado et al. (2020), Costa et al. (2020), Jian et al. (2020), Krause et al. (2020), Kshirsagar et al. (2022), Ruoso and Ribeiro (2022), Broadbent et al. (2022), ICCT (2023b), Rinaldi et al. (2023), EPE (2023b), Carvalho et al. (2023), Glyniadakis and Balestieri (2023), Krause et al. (2024), and IEA (2024). Figure 2.5 illustrates the share of the studies referring to the transport sector as whole and those focusing on road transport.

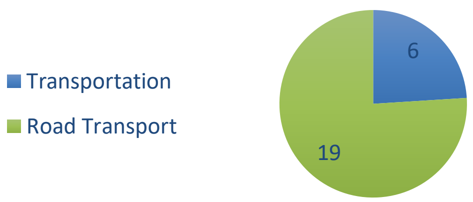


Figure 2.5 - Share of the studies referring to the transportation sector or specifically to road transport

Table 2.6 – Review of electrification and decarbonisation studies

| Reference | Focus | Objective | Region | Methodology |
|---|---|---|---|---|
| Silva (2011) | Morphological analysis; prospective scenario modelling; road transportation | Construct future scenarios in 2020 concerning the introduction of electric vehicles in São Paulo's urban traffic;<br>Identify variables and critical relations using morphological analysis to construct and analyse future scenarios;<br>Prospect alternative transportation technologies and analyse the social, economic, and environmental impacts of their adoption in São Paulo, specifically for electric vehicles in 2020. | Brazil | Morphological analysis to identify key variables and their relationships for constructing future scenarios |
| van der Zwaan et al. (2013) | Impact assessment; road transportation; scenario modelling | Investigate possible evolution pathways for the transport sector globally and in Europe under a climate change control scenario; shed light on how the transport sector should be decarbonised; investigate how and to what extent to decarbonise the transport sector in a global optimization regime; investigate the technological means with which the transport sector may best be cleared from $CO_2$ emissions | Europe (excluding Turkey and former Soviet countries) | Bottom-up linear programming model called TIAM-ECN, part of the TIMES family of models and simulates the global energy system over a 100-year period. |
| Bramstoft and Skytte (2018) | Impact assessment; scenario modelling; transport sector | Adopt a holistic energy system perspective to investigate the transportation sector as an integrated part of the energy system; analyse the future role of EVs and biofuels/renewable gases in Sweden's transportation sector; develop two scenarios for the decarbonised Swedish transportation sector in 2050: EVS (high percentage of electric transportation in light vehicles) and BIOS (high percentage of biofuel use in transportation) | Sweden | STREAM energy system model, which has a flow model for annual energy balance and a duration curve model for hourly energy balance, to investigate the transportation sector as an integrated part of the Swedish energy system. |
| Glensor and Rosa (2019) | Impact assessment; public policy; road transportation; scenario modelling | Compare the effect of a complete shift to biofuels or BEVs compared to a business-as-usual (BAU) scenario; examine the effect of applying these technologies/fuels in an extreme manner in order to identify their effects and any possible limitations, to inform further policy discussions | Brazil | LCA of urban passenger transport in Brazil, comparing a business-as-usual scenario to scenarios with a gradual shift to either biofuels or BEVs. |
| Helgeson and Peter (2019) | Impact assessment; road transportation; scenario modelling | Investigate how can the road transport sector and energy transformation technologies be integrated into an electricity market model.<br>Analyse the key interactions between the sectors and technologies, and how may these synergies contribute to decarbonisation.<br>Model the electricity and road transport sectors as well as energy transformation processes in an integrated multi-sectoral framework. | 26 EU countries plus Norway and Switzerland | Development of an integrated multi-sectoral partial-equilibrium investment and dispatch model that combines the European electricity and road transport sectors, accounting for interconnections between the sectors. |
| Zhang and Fujimori (2020) | Impact assessment; public policy; road transportation; scenario modelling | Investigate how transport electrification would impact emission trajectories and climate change, as well as what policies and strategies are needed for emission reduction and climate change mitigation. | Multinational | Global transport model to simulate transport demand, energy use, and emissions; coupling the transport model with a global economic model and climate model to capture cross-sectoral interactions; development of scenario simulations to investigate the long-term impacts of transport electrification. |

| Reference | Focus | Objective | Region | Methodology |
|---|---|---|---|---|
| Gerber Machado et al. (2020) | Barriers; impact assessment; road transportation; scenario modelling | Comprehensively analyse alternative options for the road transport sector in São Paulo, Brazil regarding GHG emissions and local pollutants (particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide), with a time horizon of 2050 | Brazil | LEAP (Long-range Energy Alternatives Planning) model, which is a simulation and optimization energy-economy model that builds energy scenarios using a hybrid of top-down and bottom-up data. |
| Costa et al. (2020) | Barriers; public policy; road transportation | Identify the strengths, weaknesses, opportunities, and threats for the expansion of electric LDVs in Brazil and provide insights that can guide public and private sector decision-making towards the expansion of EVs in Brazil. | Brazil | SWOT matrix principles applied to a survey which has been conducted among different sectors and important stakeholders with an interest in EVs. |
| Jian et al. (2020) | Impact assessment; public policy; road transportation; scenario modelling | Combine DOI and TCO methodologies to compare various road-vehicle electrification pathways; identify three NEV development scenarios (BEV, PHEV, FCV) and assess their potential impacts on transport energy demand and mix | China | Levelized cost of driving (LCOD) to compare the total cost of ownership between different vehicle technologies (BEV, PHEV, HEV, FCV, ICEV) - Bass diffusion model to simulate the future market penetration of NEVs based on the LCOD analysis - LEAP model to calculate the vehicle stock, mix, and energy consumption/mix based on the market penetration profiles |
| Krause et al. (2020) | Impact assessment; scenario modelling; public policy; road transportation | Assess the $CO_2$ reduction potential of vehicle technology and operation measures for a 2050 low-emission road transport system, aiming to contribute to the understanding of technically feasible solutions and the relative effects of different measures. | Europe | Defining a baseline scenario for 2050, then making scenario assumptions on measures that could be employed and their impacts as well as fleet penetration potential, and finally calculating 2050 road transport energy consumption and emissions under the different scenario settings, by combining the baseline of the DIONE fleet impact model with assumptions derived from expert group discussion. |
| MME/EPE (2020) | Barriers; public policy; scenario modelling; transport sector | Support the design of the long-term strategy for the expansion of the energy sector and develop recommendations and guidelines to be followed on the 2050 horizon. | Brazil | Bibliographic research and public consultation through workshops with stakeholders; development of two scenarios for energy expansion through 2050. |
| Spaniol and Hansen (2021) | Morphological analysis; public policy; transport sector | Provide a pathway toward zero emissions by systematically exploring the diverse prospects of the electrification of the seas and to power them entirely by renewable energy. The purpose is thus to provide feasible opportunities for offshore electrical recharging and thereby pathways to eliminate emissions outright. | Multinational | Morphological analysis, thematic analysis, and structural analysis. A series of strategic foresight tools are applied, which can be broken down into five steps. |

| Reference | Focus | Objective | Region | Methodology |
|---|---|---|---|---|
| Gonçalves et al. (2022) | Barriers; impact assessment; public policy; transport sector | Discuss the barriers and enablers for transport-related mitigation actions and propose a roadmap to address the policy instruments needed to accelerate decarbonisation. | Brazil | Four-phase approach: 1. Sector analysis to establish a conceptual basis. 2. Literature review to describe the Brazilian transport sector. 3. Stakeholder consultation to structure and refine the most important mitigation options, barriers, and policy instruments. 4. Results |
| Kshirsagar et al. (2022) | Impact assessment; road transportation; scenario modelling | Examines how the government in Ireland can provide pathways towards a greener Ireland by decarbonising 80% of the country by 2050. | Ireland | Three-phase approach using machine learning models: Phase 1: Use regression models to understand the carbon emitting factors for fuel-based vehicles Phase 2: Use time-series forecasting models to predict the growth of electric vehicles in the near future. Phase 3: Use time-series forecasting models to predict the potential of renewable energy (wind) to meet the growing electricity demand from electric vehicles. |
| Ruoso and Ribeiro (2022) | Barriers; public policy; road transportation | Analyse the Brazilian scenario for EV diffusion, considering the attractiveness of this technology and identifying the barriers limiting its further diffusion and the possible solutions to overcome them. | Brazil | Qualitative approach, specifically semi-structured interviews with 31 key agents in the Brazilian EV supply chain, to explore the attractiveness, barriers, and solutions around EV adoption in Brazil. |
| Broadbent et al. (2022) | Impact assessment; public policy; road transportation; scenario modelling | Project Australia's future road transport demand, vehicle mix, energy consumption and GHG emissions by 2050 by modelling different scenarios; assess the feasibility of reaching net-zero emissions in road transport in Australia; to understand the role that BEVs can play in decarbonising road transport. | Australia | The study used the iSDG-Australia integrated macroeconomic model to project Australia's future road transport demand, vehicle mix, energy consumption, and GHG emissions by 2050. The model simulated a BAU scenario and four alternative scenarios with different levels of ambition for BEV uptake and renewable electricity transition. |
| IRENA (2022) | Barriers; public policy; scenario modelling; transport sector | Provide policy makers with a conceptual overview of the global transition to electrification with renewables, presenting recent trends in relevant technologies and innovations, setting out possible long-term pathways for electrification with renewables, and identifying priority actions to enable those pathways. | Multinational | Bibliographic research; case studies in specific regions; scenario modelling built on a range of assumptions and variables, and models to simulate the energy system's transformation under different conditions. The report also includes sensitivity analysis and comparison with other scenarios. |

| Reference | Focus | Objective | Region | Methodology |
|---|---|---|---|---|
| ICCT (2023b) | Impact assessment; public policy; road transportation; scenario modelling | Explore the potential of a combination of five strategies to further reduce carbon emissions from vehicles; formulate ambitious but feasible scenarios for road vehicles and use the ICCT's Roadmap model to explore their potential to align vehicle emissions with a well-below 2°C or 1.5°C goal; leverage the expertise of other research organizations on specific aspects of the strategies, such as passenger avoid and shift, freight avoid and shift, and used vehicles | Multinational | The study involved using the ICCT's Roadmap model to explore the potential of five strategies to reduce carbon emissions from vehicles, and constructing six scenarios to analyse the impact of these strategies. |
| Rinaldi et al. (2023) | Impact assessment; public policy; road transportation; scenario modelling | Determine the optimal system configuration of a fully decarbonised energy system with electricity, heat, and hydrogen; analyze the benefits and trade-offs of deploying FCEVs vs. BEVs.<br>Examine how hydrogen storage supports FCEV deployment and industrial hydrogen decarbonisation.<br>Assess the role of power-to-hydrogen-to-power (PtHtP) as seasonal electricity storage | Switzerland and four neighbouring countries | Open-source ESM, referred to as GRIMSEL with four energy carriers (electricity, heat, hot water and hydrogen) and four sectors (residential, commercial, industrial and transport) to explore optimal pathways to decarbonise the road transport sector. |
| EPE (2023b) | Impact assessment; road transportation; scenario modelling | Project the energy demand for light vehicles (ICE, hybrid, and electric) for the 2024-2033 period, using an accounting model developed by EPE and present scenarios for the penetration of new vehicle technologies | Brazil | The study used a model developed by EPE to project the energy demand for ICE LDVs and hybrid/electric vehicles for 2024-2033, considering factors such as vehicle licensing, new technology penetration, ethanol supply, gasoline prices, and consumer preferences. Two penetration trajectories for new vehicle technologies were constructed. |
| Carvalho et al. (2023) | Impact assessment; scenario modelling; road transportation | Project the long-term (up to 2050) fleet of light vehicles in Brazil and simulate the impact of electric vehicle insertion on energy demand in three different scenarios. | Brazil | Analysis of historical data (economic, demographic, fleet) and use of machine learning regression models to project the future vehicle fleet; use of the Well-to-Wheel (WTW) approach to estimate total energy consumption across the fuel life cycle |
| Raoofi et al. (2023) | Morphological analysis; scenario modelling; transport sector | Systematically investigate and structure future technological developments within automation, electrification, and digitalization (AED) in the transportation sector - Help decision-makers gain a deeper understanding of the system structure and potential AED developments in the transportation sector - Investigate and structure development pathways within AED in the transportation sector, given the complexity and uncertainty | Sweden | Scenario planning and morphological analysis |

| Reference | Focus | Objective | Region | Methodology |
|---|---|---|---|---|
| Glyniadakis and Balestieri (2023) | Decarbonisation scenarios; light vehicle fleet; electric vehicles; ethanol fuel; emissions minimization. | Examine possible scenarios for the technological distribution of light vehicles in Brazil by 2050 to decarbonise the transportation sector.<br>Evaluate the integration of internal combustion vehicles using ethanol, gasoline hybrid vehicles, and battery-electric vehicles.<br>Assess the impact of different electric mix projections on emissions and the feasibility of electric vehicle adoption.<br>Analyze the role of ethanol as a fuel source in achieving decarbonisation targets. | Brazil | • Emissions minimization algorithm to identify potential decarbonisation scenarios.<br>• Creation of multiple scenarios based on different electric mix projections and vehicle usage patterns.<br>• Use of national databases and Brazilian electric generation mix projections.<br>• Hybrid approach combining bottom-up (technological aspects) and top-down (macroeconomic perspectives) methodologies.<br>• Optimization modeling using LINGO software to solve the proposed emission model.<br>• Comparative analysis with European projections and Brazilian decarbonisation targets. |
| Krause et al. (2024) | Impact assessment; public policy; road transportation; scenario modelling | Explore net carbon-neutral road transport options in the EU in 2050 from a WtW perspective; develop scenarios for the evolution of the road vehicle fleet composition and degree of electrification; consider technical measures to improve vehicle efficiency, transport flow, and transport volumes; combine the fleet scenarios with different alternative fuel mix scenarios for 2050 | EU | Developing 3 scenarios for the 2050 road vehicle fleet composition, with varying degrees of electrification; calculating the well-to-tank energy consumption and emissions based on 4 fuel mix scenarios and 2 electricity production pathways |
| IEA (2024) | Barriers; impact assessment; public policy; road transportation; scenario modelling | Identify and assess recent developments in electric mobility across the globe; consider what wider EV adoption means for electricity and oil consumption and greenhouse gas emissions; analyse lessons learned from leading markets, providing information for policy makers and stakeholders on policy frameworks and market systems that support electric vehicle uptake. | Multinational | Data collection and modelling tools, primarily the World Energy Model (WEM), which is a large-scale simulation model that covers the entire global energy system. The tool simulates the interactions between different elements of the energy system under various conditions. |

Regarding the objectives of the studies, 17 aimed to make impact assessments on the deployment of electrification (van der Zwaan et al., 2013; Bramstoft and Skytte, 2018; Glensor and Rosa, 2019; Helgeson and Peter, 2019; Zhang and Fujimori, 2020; Gerber Machado et al., 2020; Jian et al., 2020; Krause et al., 2020; Gonçalves et al., 2022; Kshirsagar et al., 2022; Broadbent et al., 2022; ICCT, 2023b; Rinaldi et al., 2023; EPE, 2023b; de Carvalho et al., 2023; Krause et al., 2024; IEA, 2024), 15 considered public policy or addressed policy recommendations (Glensor and Rosa, 2019; Zhang and Fujimori, 2020; Costa et al., 2020; Jian et al., 2020; Krause et al., 2020; MME/EPE, 2020; Spaniol and Hansen, 2021; Gonçalves et al., 2022; Ruoso and Ribeiro, 2022; Broadbent et al., 2022; IRENA, 2022; ICCT, 2023b; Rinaldi et al., 2023; Krause et al., 2024; IEA, 2024), and seven referred to barriers to the implementation of electrification (Gerber Machado et al., 2020; Costa et al., 2020; MME/EPE, 2020; Gonçalves et al., 2022; Ruoso and Ribeiro, 2022; IRENA, 2022; IEA, 2024).

Concerning methodological aspects, 21 of the studies used scenario modelling (Silva, 2011; van der Zwaan et al., 2013; Bramstoft and Skytte, 2018; Glensor and Rosa, 2019; Helgeson and Peter, 2019; Zhang and Fujimori, 2020; Gerber Machado et al., 2020; Jian et al., 2020; Krause et al., 2020; MME/EPE, 2020; Kshirsagar et al., 2022; Broadbent et al., 2022; IRENA, 2022; ICCT, 2023b; Rinaldi et al., 2023; EPE, 2023b; Carvalho et al., 2023; Glyniadakis and Balestieri, 2023; Raoofi et al., 2023; Krause et al., 2024; IEA, 2024), of which only two used morphological analysis (Silva, 2011; and Raoofi et al., 2023), while one study used morphological analysis but did not use prospective scenario modelling (Spaniol and Hansen, 2021).

In terms of applying morphological analysis, Silva (2011) used this technique to identify the critical variables and their relationships in order to build and analyse future scenarios for the introduction of electric vehicles in São Paulo’s urban traffic. The study identified four key groups of variables that influence an urban transportation system: scope of use, vehicle architecture and propulsion, infrastructure and business model. The study also concludes that the morphological analysis process can instigate creativity towards the development of new solutions in the adoption of electric vehicles.

Raoofi et al. (2023) used scenario planning with morphological analysis to systematically investigate and structure future technological developments within automation, electrification, and digitalization in the transportation sector. The authors state that morphological analysis is an applicable method for studying and structuring future technological pathways in the transportation sector. They also add that constructing a morphological box with many parameters and attributes while considering automation, electrification and digitalization could provide a holistic view of possible future scenarios. Finally, the study states that scenario mapping reveals that the reference scenario does not consider some relevant technological developments in automation, electrification and digitalization and should be revised accordingly.

Spaniol and Hansen (2021), used foresight as well as thematic and structural analysis, besides morphological analysis, in the context of offshore electrical recharging for ships. The authors define several variables that will influence different types of offshore charging, from charging at wind farms, to floating solar panels, to offshore container terminals; however, the study does not build future scenarios for offshore charging.

Other authors have built future scenarios for electrification and emissions, either in the context of road transport or the whole transport sector combined with buildings or industry. Bramstoft and Skytte (2018) used the STREAM energy system model to investigate the transportation sector as an integrated part of the Swedish energy system. The study finds that the scenario with a high share of EVs is the most cost-effective, reducing the total annual system cost by 9.1% compared to the reference scenario. The scenario with a high share of biofuels is the most expensive, with a 0.2% higher total annual system cost compared to the reference. The study also adds that the use of bioenergy resources in all scenarios exceeds the available domestic resources in Sweden, indicating a need for imports.

MME/EPE (2020) used bibliographic research and public consultation through workshops with stakeholders to develop two scenarios for energy expansion through 2050 in Brazil. On the adoption of EVs, the study states that there are many challenges, especially related to batteries, including their prices, supply chain reliability and technological aspects such as safety and autonomy. The study adds that battery technology may have performance improvements and prices will likely drop, leading to greater adoption in certain niches by the 2030 decade. It states that in the Brazilian case, the charging infrastructure and electricity regulation will also be relevant. Finally, it adds that electrification will start through hybrids, where the technology will be developed alongside flex fuel engines, especially in LDVs.

IRENA (2022) used scenario modelling built on a range of assumptions, variables and models to simulate the energy system's transformation under different conditions. The study states that the main questions that remain about electrification are related to its effects the energy system costs and the scope of electrification that is most cost-effective. It also adds that the costs and benefits of electrification aspects such as new investments in power generation vs. end-use flexibility and efficiency, need to be comprehensively analysed by policymakers before committing resources.

Van der Zwaan et al. (2013) used the TIAM-ECN bottom-up linear programming model to simulate the global energy system over a 100-year period. The model suggests that hydrogen will gradually become the more dominant energy carrier in the transport sector, the high costs of BEVs compared to FCEVs being the main reason. The authors state that the horizon of many analysts is no more than a few decades, instead of a full century. They reflect that EVs are a better fit for the current infrastructure than hydrogen. In the short term (one or two decades), investments are better used in charging infrastructure, due to the vast T&D network already in place. The authors conclude that "electric transportation generally proves the more expensive alternative in our long-term perspective, except when electric car costs are assumed to drop substantially". It is worth noting that this study is from 2013 and Li-ion battery prices have dropped by more than 80% since then (BloombergNEF, 2023).

Glensor and Rosa (2019) used LCA, comparing a business-as-usual scenario to scenarios with a gradual shift to either biofuels or BEVs and examine the effect of applying these technologies in an extreme manner in order to identify their effects and any possible limitations. The study's electrification scenarios offer the lowest $CO_2$ emissions compared to the biofuel scenarios. The authors also add that land use change emissions are a major contributor to higher emissions in the biofuel scenarios.

Helgeson and Peter (2019) used an integrated multi-sectoral model that combines the electricity and road transport sectors and account for interconnections between them. The model reveals that electricity and power-to-X fuels will represent 37% and 27%, respectively, of the road transport fuel mix in Europe by 2050, which will lead to an increase of 1200 TWh in electricity demand. The authors state that decoupled models fail to account for interdependencies between the electricity and road transport sectors, which can lead to the overestimation of system costs.

Zhang and Fujimori (2020) used a global transport model to simulate transport demand, energy use and emissions to investigate how transport electrification would impact emission trajectories and climate change. The model indicates that transport electrification can significantly reduce direct emissions from the transport sector, but can also lead to increased emissions in the power sector if it is not decarbonised. The study also states that the penetration of EVs can reduce the mitigation costs generated by the 2°C climate target. The study concludes that transport electrification alone is not enough to mitigate carbon emissions and must be part of a broader system decarbonisation effort.

Gerber Machado et al. (2020) used the LEAP model to analyse alternative options for the road transport sector in São Paulo, Brazil, regarding GHG emissions and local pollutants (particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide), with a time horizon of 2050. The study indicates that EVs are the best option to reduce GHG emissions and local pollutants; however, the most effective options, BEVs and FCEVs, are also the most expensive.

Jian et al. (2020) also used the LEAP model, but combined it with Levelized Cost of Driving (LCOD) and the bass diffusion model to compare different road transport electrification pathways. The model indicates that the transition to BEVs in passenger vehicles leads to a 67.6% reduction in total energy consumption by 2050, compared to 2018. The study also states that a combination of high penetration of BEVs in passenger vehicles and FCEVs in the freight vehicle segment in China will result in a 50% reduction in oil consumption by 2050. The authors add that the adoption of FCEVs can lead to a significant transformation in the energy mix of the freight transport sector.

Krause et al. (2020) developed scenarios for road transport emissions by 2050 using the DIONE fleet impact model and expert input. They found that combining fleet electrification with efficiency improvements and reduced transport activity could potentially cut $CO_2$ emissions by over 70% compared to 1990 levels, with optimistic scenarios reaching up to 90% reduction. The study emphasizes the importance of policies in driving electrification and efficiency gains. It also notes that upstream emissions could add 40% to tank-to-wheel emissions, suggesting the need for complementary policies to prevent emissions shifting to other sectors.

Kshirsagar et al. (2022) used machine learning models, including regression models and time-series forecasting models to predict the growth of EVs in the near future and the potential of renewable energy to meet the growing electricity demand from EVs. The authors find that renewable energy, particularly wind, has the potential to meet the electricity demand from the increasing number of EVs in Ireland, and that the 300 wind farms in in the country have the potential to power 26,700 EVs per day, indicating that wind energy can play a significant role in decarbonising the transport sector.

Broadbent et al. (2022) used the iSDG-Australia integrated macroeconomic model to project the country's future road transport demand, vehicle mix, energy consumption, and GHG emissions by 2050 and assess the feasibility of reaching net-zero emissions in road transport in Australia. The study finds that achieving net-zero emissions in Australia's road transport sector by 2050 is possible but requires a very high level of policy ambition, including transitioning all new vehicle sales to BEVs by 2030 and achieving 100% renewable electricity generation by 2050.

ICCT (2023b) used ICCT's Roadmap model to explore the potential of five strategies to reduce carbon emissions from vehicles, and build six scenarios to analyse the impact of the strategies. The model suggests that a combination of "five strategies could cut cumulative $CO_2$ emissions from vehicles in half through 2050 compared with a baseline scenario". The strategies are: accelerate the global transition to zero-emission vehicles; maximize the fuel efficiency of new combustion vehicles; replace old combustion vehicles faster; reduce car dependence in urban areas and improve freight logistics; and decarbonise the electricity and hydrogen used in zero emission vehicles.

Rinaldi et al. (2023) used the GRIMSEL model with four energy carriers (electricity, heat, hot water and hydrogen) and four sectors (residential, commercial, industrial and transport) to explore optimal pathways to decarbonise the road transport sector. The study finds that decarbonisation of the transport sector through electrification increases electricity demand by between 19% and 45% for an entire BEV fleet and an FCEV fleet, respectively, which leads to a 7-18% increase in photovoltaic deployment and up to a 3-fold increase in electricity storage in Switzerland. The additional electricity demand increases costs by 9-19% and emissions by 1.3 $MtCO_2$ per year. The study found that the decarbonisation of the transport sector could lead, on average, to a 90% carbon dioxide emissions reduction, the authors also conclude that "the use of hydrogen as an energy carrier to store electricity over a long period is not cost-optimal".

EPE (2023b) used a model developed by EPE to project the energy demand for ICE LDVs and hybrid/electric vehicles for 2024-2033 period and produce two penetration trajectories for the new vehicle technologies. The authors state that the pace of electrification in Brazil will be different from other countries, where "$CO_2$ emissions are the main concern", adding that the significant use of biofuels in the country allows it to have a slower transition, with improvements in vehicle efficiency being the main focus. The study also finds that flex fuel vehicles will continue to dominate the LDV market, representing around 86% of the fleet in 2033, while projecting that HEVs will continue to increase their market share, reaching 13.3%, with PHEVs and BEVs reaching 2.4% market share.

Carvalho et al. (2023) made use of analysis of historical data (economic, demographic, fleet) and machine learning regression models to project the future vehicle fleet. It also used the Well-to-Wheel (WTW) approach to estimate total energy consumption across the fuel life cycle. The study projected three scenarios, showing annual increases in electricity generation demand of 0.6%, 0.9% and 4.2% by 2050 compared to 2020. The electrification of the fleet was found to be advantageous in reducing fossil fuel use and promoting sustainability in the transport sector. In the scenario with the greatest EV insertion (60% BEV, 40% HEV by 2050), total energy consumption was projected to decrease by 25% in 2050 compared to 2020.

Krause et al. (2024) developed three scenarios for the 2050 road vehicle fleet composition, with varying degrees of electrification and calculated the well-to-tank energy consumption and emissions based on 4 fuel mix scenarios and 2 electricity production pathways. The study finds that fleet electrification is the strongest lever for reducing well-to-wheel energy consumption in road transport, with the most electrified scenarios reducing energy use by up to 80% compared to 2019. Other efficiency measures can also contribute significantly to energy savings, but their impact decreases as electrification increases. Under higher electrified scenarios, the specific fuel production pathway becomes less relevant, as the overall fuel volumes required become small.

IEA (2024) used data collection and modelling tools, primarily the World Energy Model (WEM), which simulates the interactions between different elements of the energy system under various conditions. The study states that investment is being boosted by policy support for electrification, adding that the affordability of EVs will drive the pace of the transition. Public charging deployment needs to keep up with EV adoption, especially as more electric HDVs enter the market, demanding dedicated an flexible charging. It projects that EV market share will reach 50% globally by 2035, "based on today's energy, climate and industrial policy settings". Vehicle manufacturers' pricing strategies will be crucial to make vehicles more affordable, as well as the pace of battery price decline, according to the study.

Of the 25 articles, four do not use scenario modelling, although one (Spaniol and Hansen, 2021) has been previously mentioned as it uses morphological analysis. Costa et al. (2020) uses SWOT matrix principles applied to a survey conducted among different sectors and stakeholders with an interest in EVs. The author states that electric LDVs are the best option for low carbon passenger mobility in Brazil, but their expansion requires government regulation, incentive policies and adequate infrastructure. Both consumers and society will benefit the most from the expansion of electric vehicles due to their low emissions and total cost of ownership, according to the study.

Gonçalves et al. (2022) use expert opinion and bibliographic research to discuss the barriers and enablers for transport mitigation actions. The paper suggests that electric mobility should be the main mitigation measure for the Brazilian transport sector, and that 80% of the instruments needed to overcome barriers to electric mobility can be addressed in the next two years, led by the Ministries of Regional Development and Infrastructure, and development banks. The Study also finds that improvements to public transport can be addressed in the short term, and that these two main measures (electric mobility and public transport improvements) should focus on metropolitan areas, while regional transport should benefit from existing biofuels and high-capacity infrastructure policies.

Ruoso and Ribeiro (2022) used semi-structured interviews with key agents in the Brazilian EV supply chain, to explore the attractiveness, barriers, and solutions around EV adoption in Brazil. The authors find that the high acquisition cost of EVs is the main barrier to their adoption, which is exacerbated by the lack of adequate public policy incentives. Barriers related to the local EV market and supply chain are key determinants for EV advancement, requiring collaboration between government and industry to invest in R&D for battery and charging infrastructure improvements.

The study by Glyniadakis and Balestieri (2023) explores decarbonisation scenarios for Brazil's LDV fleet by 2050. It discusses the potential integration of internal combustion engine vehicles (ICEVs) using ethanol, HEVs, and BEVs within the national energy mix. An emissions minimisation algorithm was used to project various scenarios, including fleet growth and energy generation conditions. The findings show that a 10% integration of BEVs, coupled with widespread ethanol use, could achieve a 58% emissions reduction by 2050. Further, improving the ethanol production chain's efficiency could push decarbonisation efforts up to 77%. The study highlights the critical role of biofuels in the energy transition alongside electrification. This study is particularly relevant to the present dissertation, as it identifies key barriers, such as technology costs and energy mix limitations, that need to be overcome for the successful electrification of Brazil's light vehicle fleet by 2050.

Table 2.7 presents a comprehensive compilation of 46 variables identified through a systematic analysis of studies reviewed (Table 2.5). This mapping served as a reference framework for the selection of key variables subsequently incorporated into the structural analysis during the scenario construction phase (Chapter 4).

Table 2.7 – Mapping variables associated with transport electrification and decarbonisation

| Variable | Description | References |
|---|---|---|
| Road restrictions | High pollutant vehicle restrictions in city centres; EV exemption from tag rotation | Silva (2011) |
| EV policy support | Governmental and institutional measures, regulations, and incentives designed to encourage the adoption and use of EVs. | Zhang and Fujimori (2020); Costa (2020); IEA (2024) |
| ICE sales phaseout | Gradual ban on ICE sales | Zhang and Fujimori (2020); Broadbent et al. (2022); ICCT (2023); IEA (2024) |
| Phaseout of older vehicles | Vehicle replacement schemes, to make it more attractive for ICE vehicle owners to switch to EVs | ICCT (2023) |
| GDP | Expected economic growth | Bramstoft and Skytte (2018); MME/EPE (2020); Broadbent et al. (2022); de Carvalho et al. (2023); IEA (2024) |
| Income per capita | Average income earned per person | MME and EPE (2020); Broadbent et al. (2022) |
| Vehicle purchase cost | Cost to purchase a new EV | van der Zwaan et al. (2013); Costa (2020); Jian et al. (2020); IRENA (2022); IEA (2024) |
| Vehicle operational cost | Cost to operate an EV | van der Zwaan et al. (2013) |
| Battery purchase cost | Cost to purchase a new battery | Costa (2020); IRENA (2022); IEA (2024) |
| EV cost compared to ICE | Cost of purchasing and operating an EV compared to an ICE vehicle | Jian et al. (2020) |
| Resale value | Resale value of EVs | Costa (2020) |
| Charging infrastructure investment | Cost and revenue related to EV charging infrastructure | Spaniol and Hansen (2021); IRENA (2022); Rinaldi et al. (2023) |
| Total vehicle sales | Total vehicle sales in the country per category (ICE, HEV, PHEV, BEV, FCEV) | Glensor and Rosa (2019); MME and EPE (2020); Kshirsagar et al. (2022); Broadbent et al. (2022); EPE (2023); de Carvalho et al. (2023) |
| Total vehicle fleet | Total vehicle fleet in the country per category (ICE, HEV, PHEV, BEV, FCEV) | Bramstoft and Skytte (2018); Krause et al. (2020); MME/EPE (2020); Rinaldi et al. (2023); Carvalho et al. (2023); Raoofi et al. (2023); Krause et al. (2024); Glyniadakis and Balestieri (2023) |
| Fuel trade | Fuel supply, demand and related prices | Glensor and Rosa (2019); Helgeson and Peter (2019); Gerber Machado et al. (2020); Costa (2020); Jian et al. (2020); IRENA (2022); EPE (2023); de Carvalho et al. (2023); Krause et al. (2024); IEA (2024) |

| Variable | Description | References |
|---|---|---|
| Electricity trade | Electricity supply, demand and related prices | Glensor and Rosa (2019); Helgeson and Peter (2019); Gerber Machado et al. (2020); Costa (2020); Jian et al. (2020); Rinaldi et al. (2023); IEA (2024) |
| e-fuel trade | E-fuel supply, demand and related prices | Gerber Machado et al. (2020); Costa (2020); IRENA (2022); Krause et al. (2024) |
| EV supply chain | Supply chain for EV and battery production | Costa (2020) |
| Business model | Development of V2X business models | Silva (2011); Costa (2020) |
| Transport demand | Total demand for transport, including private trips, services, public transport and freight | MME and EPE (2020); ICCT (2023) |
| Modal shift | Shift to other modes of transport, including rail, public transport, carsharing, etc. | Silva (2011); Bramstoft and Skytte (2018); Krause et al. (2020); MME and EPE (2020); ICCT (2023); Raoofi et al. (2023) |
| Public awareness/preference towards EVs | Consumer behaviour towards owning an EV compared to an ICE vehicle | Costa (2020); Spaniol and Hansen (2021); EPE (2023); IEA (2024) |
| Range anxiety | Fear of running out of battery and having nowhere to recharge | Costa (2020) |
| km travelled per capita | Avg. kilometres travelled per person in the country | Jian et al. (2020); de Carvalho et al. (2023) |
| Population size/growth | Size of the population and its growth in the studied period | MME/EPE (2020); Broadbent et al. (2022); de Carvalho et al. (2023); IEA (2024) |
| Vehicle energy storage | The energy storage system used in vehicles, including ICE vehicles, HEVs, PHEVs, BEVs and FCEVs. | Silva (2011); van der Zwaan et al. (2013) |
| Vehicle autonomy | The distance that a vehicle can run before having to recharge or refuel | Silva (2011); van der Zwaan et al. (2013); Costa (2020); Rinaldi et al. (2023) |
| Fuelling/charging time | The time it takes for a vehicle user to recharge or refuel a vehicle | van der Zwaan et al. (2013); Costa (2020) |
| CCS technology usage | The development of CCS technology and usage in the studied period | van der Zwaan et al. (2013) |
| Bio-component of fuels | Share of flex-fuel and flex-fuel hybrid vehicle sales | Glensor and Rosa (2019) |
| Vehicle efficiency | How effectively a vehicle converts fuel or electricity into useful energy to propel the vehicle | Glensor and Rosa (2019); Jian et al. (2020); Krause et al. (2020); Costa (2020); ICCT (2023); Carvalho et al. (2023); Krause et al. (2024); Glyniadakis and Balestieri (2023) |
| Vehicle lifetime | Period during which a vehicle remains functional and is used for its intended purpose | Glensor and Rosa (2019); Jian et al. (2020) |
| Charging infrastructure deployment | The amount of charging infrastructure available for EV users | Silva (2011); Costa (2020); Raoofi et al. (2023); IEA (2024) |

| Variable | Description | References |
|---|---|---|
| Transmission & Distribution network efficiency | The effectiveness with which electrical energy is transported from power plants to end-users through the electrical grid | Costa (2020); Jian et al. (2020); de Carvalho et al. (2023) |
| Energy access | Share of the population with access to energy services | IEA (2024) |
| Renewables generation supply | Share of energy generation that is renewable | Zhang and Fujimori (2020); Costa (2020); Kshirsagar et al. (2022); Broadbent et al. (2022) |
| Building energy efficiency | The optimization of energy use and design in buildings to provide the necessary services while minimizing energy consumption, including EV charging stations with V2B capabilities | Broadbent et al. (2022) |
| Electricity supply | Amount of electricity supplied to the grid | Helgeson and Peter (2019); Rinaldi et al. (2023); IEA (2024); Glyniadakis and Balestieri (2023) |
| Fuel supply | Amount of fuel supplied in a region | Helgeson and Peter (2019); EPE (2023); IEA (2024) |
| $CO_2$ fleet emissions | $CO_2$ emissions resulting from a region's total vehicle fleet | Silva (2011); Glensor and Rosa (2019); Helgeson and Peter (2019); Costa (2020); Krause et al. (2020); Spaniol and Hansen (2021); Kshirsagar et al. (2022); Rinaldi et al. (2023); Glyniadakis and Balestieri (2023) |
| NOx fleet emissions | NOx emissions resulting from a region's total vehicle fleet | Glensor and Rosa (2019); Glyniadakis and Balestieri (2023) |
| PM fleet emissions | PM emissions resulting from a region's total vehicle fleet | Silva (2011); Glensor and Rosa (2019); Costa (2020) |
| Land for biofuel feedstocks | Amount of land used to produce biofuel feedstocks | Glensor and Rosa (2019) |
| Carbon footprint of electricity production | Total amount of $CO_2$ emitted during the generation of electricity | Krause et al., (2024) |
| Battery recycling/reuse rates | The rate at which EV materials are recycled or reused | Glensor and Rosa (2019); Spaniol and Hansen (2021); Raoofi et al. (2023) |
| CCS usage | Amount of $CO_2$ captured and stored by the use of CCS in the studied period | van der Zwaan et al. (2013); Helgeson and Peter (2019) |

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## 2.8
## Final considerations

This chapter has provided an overview of road transport electrification technologies, their potential applications, and limitations. The examination of EV propulsion systems, energy storage technologies, charging systems, and infrastructure development offers a foundation for understanding the current state and future prospects of transport electrification in the context of decarbonisation efforts.

The review of EV categories demonstrates the range of electrification options available. Each category presents distinct advantages and challenges in terms of energy efficiency, environmental impact, and market readiness. The analysis of energy storage technologies, highlights the rapid progress in this field. However, it also underscores the need for continued research and development to address issues such as energy density, charging speed, and environmental concerns related to battery production and disposal.

The examination of charging systems and infrastructure reveals the complexities involved in transitioning to an electrified transportation system. The development of charging networks, the integration of smart charging technologies, and the potential for vehicle-to-grid (V2G) systems present both opportunities and challenges for grid management and energy efficiency. The discussion of these topics illustrates the interdependence of technological advancement, infrastructure development, and policy support in facilitating the widespread adoption of EVs.

The global and Brazilian electrification outlooks presented in this chapter provide context for understanding the current state and potential trajectory of transport electrification. The global trend towards increased EV adoption, driven by technological improvements, policy support, and growing environmental awareness, contrasts with the more nuanced situation in Brazil. The country's unique position, with its established ethanol industry and predominantly renewable electricity mix, presents both opportunities and challenges for electrification efforts.

The review of 25 selected studies on transport electrification, decarbonisation, and adoption barriers offers a comprehensive view of the current research landscape. These studies highlight the multifaceted nature of the transition to electric mobility, encompassing technological, economic, social, and environmental dimensions. The diversity of methodologies employed in these studies - from scenario modelling to lifecycle assessments - demonstrates the complexity of analyzing the impacts of transport electrification.

Several themes emerge from this literature review. First, the potential for EVs to reduce GHG emissions is significant, but highly dependent on the carbon intensity of the electricity grid. Second, the economic viability of EVs remains a key concern, with high upfront costs and uncertain resale values presenting barriers to adoption. Third, the development of charging infrastructure is critical for widespread EV adoption, particularly for addressing range anxiety among potential users. Fourth, policy support plays a vital role in accelerating the transition to electric mobility, through measures such as purchase incentives, emissions regulations, and investment in charging infrastructure.

The Brazilian context presents unique considerations for transport electrification in general and for the LDV fleet in particular. The country's high renewable energy share in its electricity mix provides a favourable foundation for the environmental benefits of EVs. However, the established ethanol industry and the prevalence of flex-fuel vehicles introduce additional factors to consider in the transition to electrification. The balance between promoting EVs and supporting the ethanol industry represents a distinctive challenge for Brazilian policymakers and stakeholders.

As the field of transport electrification continues to evolve rapidly, ongoing research will be necessary to address emerging challenges and opportunities. Future studies may focus on optimizing the integration of EVs with renewable energy sources, developing more efficient and environmentally friendly battery technologies, and designing policy frameworks that effectively balance the various goals of decarbonisation, economic development, and social equity in the context of transport electrification.

Finally, with the comprehensive bibliographic research performed, the research gap becomes evident, as no previous study has combined morphological analysis, prospective scenario modelling and forecasting techniques to assess the impact of electrification on decarbonisation of the road transport sector.

# 3
# Prospective scenario modelling for assessing the impacts of electrification on the decarbonisation of Brazil's light-vehicle fleet

This chapter presents a comprehensive conceptual framework for prospective scenario modelling, designed to assess the potential impacts of electrification on the decarbonisation of Brazil's LDV fleet. The methodology employed is a sophisticated hybrid approach, combining foresight and forecasting techniques. This methodological synthesis facilitates the construction of five distinct decarbonisation scenarios, providing a nuanced exploration of possible future trajectories for Brazil's transportation sector. By leveraging both qualitative and quantitative methods, this framework offers a robust foundation for analysing the complex interplay of technological, economic, and policy factors that will shape the future of vehicle electrification in Brazil.

There are several approaches and methods for constructing prospective scenarios, all with the objective of obtaining configurations of alternative medium and long-term futures, which should be used as instruments in planning at the macro level (countries and regions), at the sectoral level (sectors of the economy) and at the organizational (public, private and third sector organizations).

In this dissertation, a mixed methodological approach was employed for the construction of alternative prospective scenarios, which combines foresight and forecast approaches. Foresight typically refers to a more qualitative, long-term, and exploratory approach to anticipating future possibilities, while forecast refers to more quantitative, often predictions based on historical data and trends. It includes statistical methods, time series analysis, and predictive modelling.

Using both together can balance the strengths of each approach, allowing for both broad, creative thinking about the future and more concrete, near-term planning. This combined approach consists of the following eight steps:

- Definition of the guiding questions for constructing scenarios and time horizon to be considered (Schwartz, 1998);
- Definition and classification of key variables, through the use of the structural analysis technique (Godet, 2000);
- Identification of the main stakeholders and influencers of the scenarios (Godet, 2000);
- Characterization of the current situation (2024) and identification of future determinants in the considered horizon (Godet, 2000);
- Construction of prospective scenarios, using the morphological analysis (Zwicky, 1969). This step also includes the verification of the consistency and plausibility of the configurations and the selection of the most probable scenarios;
- Estimating the size of the LDV fleet and the potential reduction of GHG emissions (Hair et al., 2019;
- Description of the prospective scenarios, including: philosophy, trajectories in the periods 2025-2030; 2031-2040, and 2041-2050 (Godet, 2000);
- Analysis of barriers to implementing electrification of the LDV fleet in Brazil by 2050 and the strategic implications for overcoming them within this time horizon.

Figure 3.1 shows the conceptual framework for prospective scenario modelling, designed to assess the potential impacts of electrification on the decarbonisation of Brazil's LDV fleet, considering the horizon of 2050. Next, the eight steps are described according to this schematic representation of the conceptual framework for prospective scenario modelling.

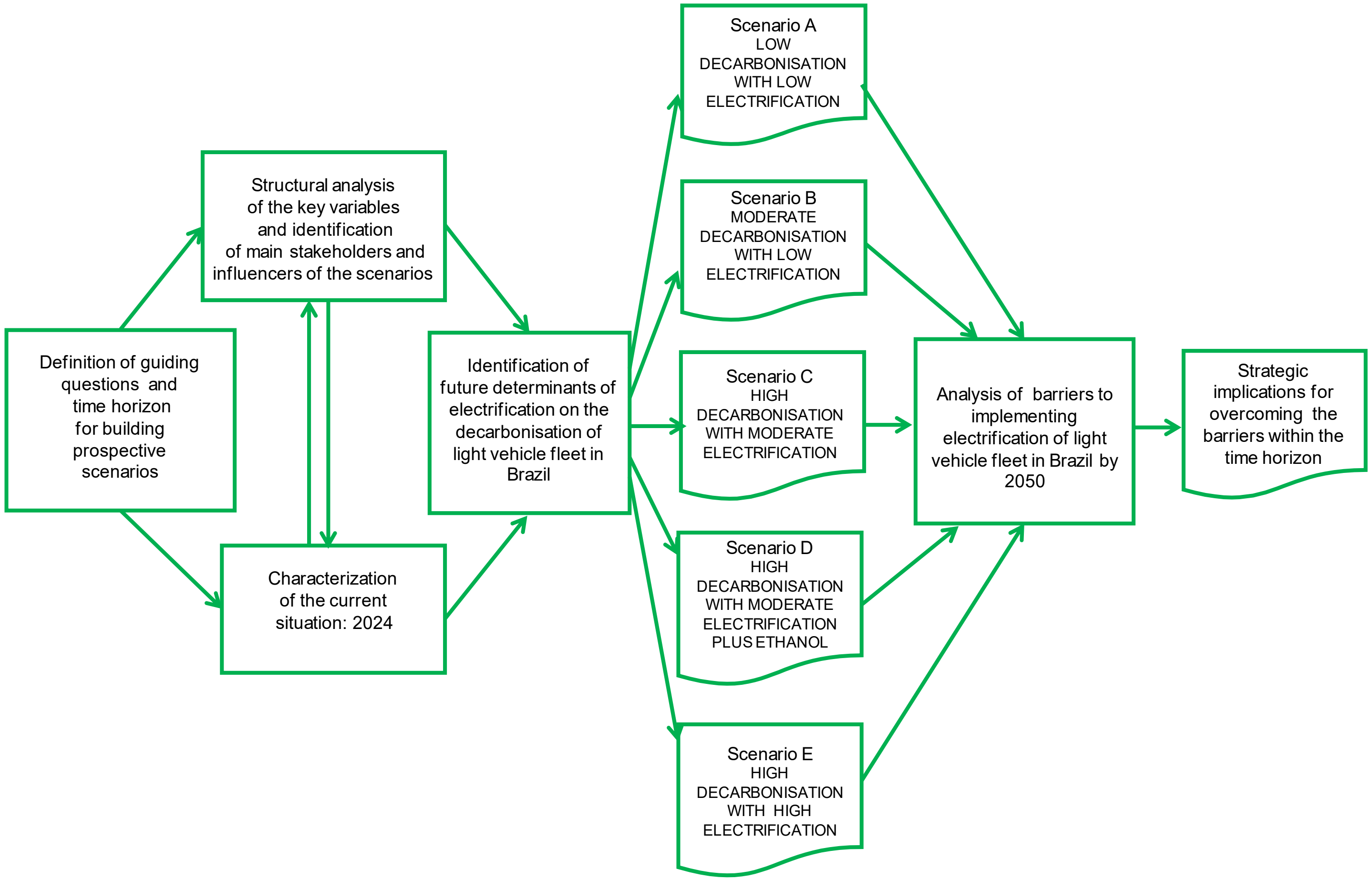


Figure 3.1 – Conceptual framework for prospective scenario modelling to assess the potential impacts of electrification on the decarbonisation of Brazil's light vehicle fleet

### 3.1. Definition of the guiding questions and time horizon

The first step in constructing prospective scenarios is to define the guiding questions, which shape the analysis and provide focus (Schwartz, 1998). These questions should address key concerns about the future, uncertainties, and the long-term vision for the system evolution.

The time horizon should be determined according to the nature of the subject, allowing adequate time for significant changes or trends to develop. A time horizon of 2035–2050 is often used for energy and environmental scenarios as it allows the modelling of technological adoption and regulatory shifts.

### 3.2. Definition and classification of key variables: use of the structural analysis

With guiding questions established, the next step is mapping the complex system to be scenarized. Structural analysis is used to identify and classify the key variables that will shape the future of the system (Godet, 2000). Structural analysis, using the MICMAC (Cross-Impact Matrix – Multiplication Applied to Classification) method (Lipsor, 2024), is essential to identify and classify the key variables that will shape the future scenarios.

The process begins by listing relevant variables and analyzing their direct and indirect relationships. These variables are classified based on their influence and dependence, revealing key drivers and dependencies within the system. The matrix is then elevated to a power to compute indirect impacts, which helps identify "hidden variables" that play a crucial role in the system's evolution. This technique provides a comprehensive understanding of the system's dynamics and helps refine the scenario building process.

Based on Godet's methodology and the structural analysis approach, these variables can be classified as follows:

- Determinant variables (or driving forces): These are the most influential variables with low dependence on others. They are located in the upper-left quadrant of the influence-dependence map. Determinant variables are key drivers of the system, strongly impacting other variables while being relatively unaffected by them. They are often external factors that shape the overall environment.

- Surrounding variables: These variables are also located in the upper-left quadrant, just below the determinant variables. They have high influence but slightly more dependence than determinant variables. Surrounding variables are complementary to the determinant variables and help to provide a more complete picture of the system's driving forces.
- Relay variables: Located in the upper-right quadrant, relay variables have both high influence and high dependence. They are often unstable and can act as catalysts or breaking points in the system. Relay variables are critical for the system's dynamics, as changes in these variables can have significant ripple effects throughout the entire system.
- Regulatory variables: These variables are found in the central area of the influence-dependence map. They have moderate levels of both influence and dependence. Regulatory variables play a crucial role in the system's functioning, often serving as "levers" that can be manipulated to affect the system's behaviour. They are important for fine-tuning strategies and policies.
- Resultant variables: Located in the lower-right quadrant, resultant variables have low influence but high dependence on other variables. They are sensitive to changes in the determinant and relay variables. Resultant variables often represent the outcomes or effects of the system's dynamics, making them useful indicators of the system's overall state.

Understanding these variable types helps in identifying which factors are most crucial for shaping the future of the system under study, and which are more likely to be impacted by changes in other variables. This classification is vital for developing coherent and plausible scenarios, as well as for formulating effective strategies.

## 3.3.
## Definition of key stakeholders and influencers of the scenarios

Identifying stakeholders is a critical step in scenario building, as they represent the entities affected by or capable of influencing the system under study. Stakeholders may include government agencies, industry players, environmental organizations, consumers, and technological developers. Understanding their roles, interests, and power dynamics helps outline potential interactions and conflicts within the system, which must be considered in prospective scenarios.

This step maps out the key actors who can influence the system's future. It involves: (i) identifying all relevant stakeholders; (ii) analyzing their objectives, motivations, and power; (iii) understanding potential alliances and conflicts between actors; and determining how stakeholders may impact key variables.

## 3.4. Characterization of the current situation (2024) and future determinants in the considered horizon

To develop scenarios, it is crucial to understand the current state of the system in 2024 and identify future determinants such as trends, invariants, and critical uncertainties. This provides a baseline understanding of the system and identifies factors that will shape its future evolution. It includes: (i) analysing the current state of key variables; (ii) identifying historical trends and emerging issues; (iii) determining "predetermined elements" likely to persist; and (iv) highlighting critical uncertainties that could drive change.

Godet (2000) defines tendencies as predictable, long-term events, while invariants refer to elements that remain constant over time, such as physical laws or demographic factors. Critical uncertainties are factors whose future development is uncertain but may significantly impact the system. These determinants form the basis for exploring different possible futures (see Subsection 3.6).

## 3.5. Construction of prospective scenarios: use of morphological matrices

General morphological analysis (GMA), created by Zwicky (1969), is an analytical-combinatorial technique, which is based on the decomposition of a problem, or object of analysis, in its attributes. It aims at identifying, structuring, and investigating the total set of possible relationships contained in a given multidimensional and complex problem.

Adopting the technique of cross-consistency assessment, one can identify the possible solutions that actually exist, eliminating the unreasoned solution combinations rather than reducing the number of parameters involved (Ritchey, 2011, 2012). GMA has been applied successfully in engineering design, strategic planning, prospective scenario modelling, technological and business foresight, organizational development, and policymaking.

GMA is a method for identifying and investigating the whole set of possible relationships in any given, multidimensional, and complex problem that can be parameterized. The logic of problem decomposition is to deal with less complex issues than the original system, thus enabling a deeper analysis of the parts (i.e., variables and parameters considered).

Through systematic analysis of the possible states, one can create a universe of prospective scenarios (Figure 3.2).

| **Scenario – [title]** | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Hypothesis (H)** | | | | |
| Variable 1 | H1 | H2 | H3 | | |
| Variable 2 | H4 | H5 | H6 | | |
| Variable 3 | H7 | H8 | H9 | | |
| Variable 4 | H10 | H11 | H12 | | |
| Variable 5 | H13 | H14 | H15 | | |
| Variable 6 | H16 | H17 | H18 | H19 | H20 |
| Variable 7 | H21 | H22 | H23 | H24 | H25 |
| Variable 8 | H26 | H27 | H28 | | |
| Variable 9 | H29 | H30 | H31 | H32 | H33 |
| Variable 10 | H34 | H35 | H36 | H37 | H38 |

Figure 3.2 – A generic multidimensional matrix applicable to the construction of prospective scenarios
**Note:** The colour-coded hypotheses in this morphological matrix refer to a consistent and plausible configuration for the future of the system under prospective analysis.

The basic premise of choosing GMA is that a complex problem—such the electrification of light vehicle fleet in Brazil by 2050, which undergo a systematic analysis of the possible states that key parameters may assume.

This method comprises five (iterative) steps, as follows: (i) formulating the research problem to be solved very concisely; (ii) identifying all parameters that might be of importance for solving the problem; (iii) constructing the morphological matrix, which contains all parameters and their possible states; (iv) evaluating the consistency of possible morphological conceptions in relation to the purpose to be achieved; and (v) defining and choosing consistent conceptions of suitable solutions.

For the purpose of this dissertation five morphological matrices will be created corresponding to distinct decarbonisation scenarios, as will be demonstrated in Chapter 4.

To complete the morphological matrices corresponding to each scenario, it was essential to project the composition of the light-duty vehicle fleet, particularly focusing on varying levels of EV penetration. This step was crucial for establishing the hypotheses associated with two key variables, namely: (i) share of electric vehicles in the light vehicle fleet (EVSH); and (ii) potential reduction of greenhouse gas emissions (GHGE) due to electrification of the light vehicle fleet in Brazil.

### 3.6. Estimating the size of the light vehicle fleet and the potential reduction of GHG emissions

A prospective analysis of macroeconomic variables $(M_s)$ involves defining and estimating them over the time horizon $(t_h)$, which is defined for a macroeconomic scenario. Initially, the most relevant macroeconomic variables are identified, and those with the highest correlation with the number of vehicles in the fleet are selected. Next, the chosen variables are estimated for horizon $t_h$, considering the size of the fleet and the macroeconomic scenario. To determine which macroeconomic variables should be used, the historical series can be truncated using more recent data to obtain better correlations between the size of the fleet and these variables. The time variable $t_1$ represents the first data point of the truncated historical series, whereas $t_n$ refers to the last data point in this series $(t_1, t_2, \dots, t_n)$.

From collected historical data and prospective analysis of the size of the population and the macroeconomic variables $(M_a)$, an econometric model is developed to estimate the size of the fleet $(F)$. This model is based on regression analysis between the fleet $(F)$, citizen population $(P)$ and the macroeconomic variables $(M_a)$. In Eq. 1, the function f (.) is obtained from a linear regression.

$$F(t) = f\big(M_a(t); P(t)\big), \quad (1)$$

where $t = t_1, t_2, \dots, t_n$.

The linear regression can be performed using MS Excel, where statistical tests can be conducted to validate the model, including correlation verification, analysis of variance (ANOVA), and regression coefficient (t-test). Once validated, the size of the fleet $(F)$ is calculated for each macroeconomic scenario using the regression model established by Eq. 1. Thus, the size of the fleet $(F)$ related to the scenario $M_a$ as within the time horizon $(t_h)$ can be calculated by Eq. 2.

$$F(t_h) = f\big(M_a(t_h); P(t_h)\big), \tag{2}$$

where $h = n + 1, n + 2, \ldots, n + k$, $k$ is duration of the time horizon.

The EV fleet can be projected based on premisses for an ICE sales phaseout. A hypothetical phaseout $PO$ can be assumed to happen at time $t_{PO}$, where all vehicle sales $S_V$ are EV sales $S_{EV}$, where $PO$: $S_v = S_{EV} = S_{EV}(t_{PO})$. The average quantity of historical total vehicle sales from a time period defined by the analyst's choice, can be assumed to be the same by the time the phaseout happens. The EV sales at a given year $S_{EV}(t)$ can be estimated by the linear interpolation between the last historical year $S_{EV}(t_0)$ and the phaseout year $S_{EV}(t_{PO})$, according to Eq. (3):

$$S_{EV}(t) = S_{EV}(t-1) + \frac{t-t_0}{t_{PO}-t_0} \cdot \big(S_{EV}(t_{PO}) - S_{EV}(t_0)\big). \tag{3}$$

The EV fleet ($F_{EV}$) in a given year ($t$) is projected by accumulating the EV sales ($S_{EV}$) given by Eq. (4):

$$F_{EV}(t) = F_{EV}(t-1) + S_{EV}(t). \tag{4}$$

The ICE fleet can be obtained by subtracting the EV fleet from the vehicle fleet, according to Eq. (5):

$$F_{ICE}(t) = F(t) - F_{EV}(t) \tag{5}$$

To estimate the fleet of the different EV categories in the prospective scenarios, different hypotheses are defined for the share of the fleet that each category would have at the study's horizon based on the literature. Therefore, the fleet of each vehicle category can be estimated for each year in the study's horizon. Table 3.1 presents an example of a what a study with five scenarios would look like.

Table 3.1: EV fleet share in 2050 for each scenario

| | ICE | HEV | HEV Flex | PHEV | BEV |
|---|---|---|---|---|---|
| Scenario A | % | % | % | % | % |
| Scenario B | % | % | % | % | % |
| Scenario C | % | % | % | % | % |
| Scenario D | % | % | % | % | % |
| Scenario E | % | % | % | % | % |

With each vehicle category's share of the fleet at the end of the study's horizon, a linear interpolation of each category's fleet can be performed from the current time to the end of the study's horizon in each scenario.

### 3.6.1. Vehicle consumption

With the total vehicle fleet and the share of the fleet of each vehicle category in each year of the study's horizon, the next step is to estimate the vehicle consumption by fuel. In Brazil's case: gasoline, ethanol and electricity. The average consumption rates of the best-selling vehicles in each category in a period of time, chosen by the study's analyst, can be used to calculate the average consumption for the categories. In the case of Brazil, the consumption rates given by INMETRO (2024) can be used. It is important to consider the fuel blend used in the fleet, in case gasoline is blended with a biofuel, for instance. In this case, Eq. (6) and (7) are suggested:

$$C_{ICE,g} = C_{ICE} \cdot P_g \tag{6}$$

$$C_{ICE,e} = C_{ICE} \cdot P_e, \tag{7}$$

where $C_{ICE,g}$ is the gasoline consumption for ICEs, $C_{ICE}$ is the total consumption of ICEs, $P_g$ is the proportion of gasoline in the fuel, $C_{ICE,e}$ is the ethanol consumption for ICEs and $P_e$ is the proportion of ethanol in fuel consumption.

In the case of PHEVs, consumption by each fuel can be calculated by Eq. (8)-(10).

$$C_{PHEV_g} = C_{PHEV} \cdot U_{ICE} \cdot (1 - R_e) \cdot EFF \tag{8}$$

$$C_{PHEV_e} = C_{PHEV} \cdot U_{ICE} \cdot R_e \cdot EFF \tag{9}$$

$$C_{PHEV_b} = C_{PHEV} \cdot U_b \cdot (1 - EFF), \tag{10}$$

where $C_{PHEV,g}$ is the gasoline consumption in PHEVs, $C_{PHEV}$ is the total consumption of PHEVs, $U_{ICE}$ is the ratio of the usage of the ICE over the electric motor, $R_e$ is the rate of ethanol in the engine, $EFF$ is the ratio of the efficiency of the ICE over the efficiency of the electric motor in converting energy from the source to the wheels, $C_{PHEV_e}$ is the ethanol consumption in PHEVs, $C_{PHEV_b}$ is the electricity consumption. In the BEV case, all consumption comes from electricity.

### 3.6.2 Calculating GHG emissions

To calculate the total yearly emissions ($GHG(t)$), the projected fleet of each vehicle category (ICE, HEV, HEV Flex, PHEV and BEV), in each year ($F_{cat}(t)$) up to the study's horizon can be multiplied by the average total annual distance driven annually by vehicle in the fleet ($D_t$). This results in the total annual distance driven each year by vehicle category. The total annual distance driven is then multiplied by the consumption of each fuel (gasoline, ethanol and electricity), by each vehicle category in each year ($C_{es,cat}(t)$), up to the horizon, resulting in the total energy consumption by each fuel in every year. This energy consumption is then multiplied by the yearly emission factors for each fuel ($EMF_{es}(t)$). The calculation is expressed in Eq. (11) and (12).

$$GHG(t) = \sum_i F_{cat_i}(t) \cdot D_i(t) \cdot C_{es,cat,_i}(t) \cdot EMF_{es,_i}(t) \tag{11}$$

$$GHG_{total} = \sum_t GHG(t) \tag{12}$$

By calculating vehicle emissions and modelling different rates of EV adoption, it is possible to explore a range of outcomes, from minimal EV uptake to more ambitious electrification scenarios. These projections enable the assessment of the extent to which increasing the proportion of EVs could contribute to overall emissions reductions. The interplay between these two variables—EVSH and GHGE—forms the foundation for identifying plausible pathways and constraints for decarbonisation within the time horizon considered. Thus, this stage is critical for ensuring that the scenario hypotheses are both coherent and grounded in realistic projections of fleet evolution and emissions impacts.

## 3.7.
## Description of prospective scenarios: three trajectories

Following Godet’s scenario-building methodology, this step refers to the description of prospective scenarios encompassing fundamental philosophical underpinnings and projected trajectories across three distinct temporal phases (2025-2030, 2031-2040, and 2041-2050). These phases are strategically aligned with pivotal energy and environmental policy milestones in Brazil's national agenda, ensuring contextually relevant and temporally structured analysis. They are:

- 2030: Energy efficiency targets set by the National Energy Efficiency Plan (PNEf) (10% of energy consumption) and Brazil's NDC to meet emission reduction targets agreed upon at COP 21 in Paris;
- 2040: Proposed phase-out of the sale of internal combustion engine (ICE) vehicles in Brazil;
- 2050: Target year of the latest National Energy Plan published by the Energy Research Company (EPE).

This description highlights the driving forces and key events that shape each scenario, providing a clear understanding of how the future might unfold. Several components are essential for the construction and description of the prospective scenarios:

- Philosophy: The philosophy of a scenario reflects its underlying assumptions, values, and guiding principles. It defines the overall approach to how the future is envisioned, and determines whether the scenario is optimistic, pessimistic, or neutral. The philosophy sets the tone and orientation of the scenario by considering which trends or disruptions are prioritized;
- Scene: Scene represents the specific conditions and context at the starting point of the scenario. It typically involves a snapshot of the present situation or immediate future, providing the baseline from which the scenario develops. The scene outlines the initial drivers, constraints, and challenges that must be addressed over time;
- Trajectory: It refers to the pathway or sequence of events that lead from the current situation to the future scenario. This is a detailed roadmap of key transitions, shifts, and milestones. The trajectory can be broken down

into different time periods, such as 2025-2030, 2031-2040, and 2041-2050, to highlight how the scenario evolves over the medium and long term.

- Tendencies and invariants: Within each scenario, tendencies and invariants were identified. These factors will likely evolve steadily over time (tendencies) or remain constant (invariants). They provide a certain degree of certainty and are essential for building plausible and consistent scenarios.
- Critical uncertainties: Scenarios often hinge on certain unknown factors or uncertainties that can significantly alter the future. These uncertainties may involve technological breakthroughs, political decisions, and social shifts, which can dramatically affect the trajectory. Scenarios explore these variables by considering different possible outcomes of these critical uncertainties.
- Plausibility and consistency: Throughout the scenario-building process, it was necessary to ensure that each scenario was internally consistent and plausible. This involves cross-verifying assumptions, variables, and interactions to confirm that the scenario follows logical and realistic patterns, given the current understanding of the trends and uncertainties. This structured approach allows for the creation of robust, multifaceted scenarios that help key actors involved in anticipating and preparing for various futures, particularly in complex fields such as energy and transportation.

## 3.8. Analysis of barriers to implementing electrification of light vehicle fleet in Brazil and strategic implications

The final step involves identifying barriers to the successful electrification of Brazil's light vehicle fleet by 2050, such as regulatory challenges, economic and social constraints, technological limitations, industrial and environmental barriers. Given the barriers outlined above, several strategic implications emerge, guiding policymakers and stakeholders on actions to facilitate the transition. By way of illustration, some recommendations are here presented;

- Policy interventions: Governmental policies are needed to provide clear, long-term incentives for EV adoption, including purchase subsidies, tax exemptions, and industrial policies to support local EV manufacturing.

Setting clear regulatory targets for EV penetration by 2035 and 2050 will help align stakeholder efforts.

- Infrastructure development: Investments in charging infrastructure must be prioritized, including both public and private sector involvement. Government initiatives should focus on incentivizing the construction of urban charging stations and establishing fast-charging corridors along major highways.
- Technological innovation: To overcome technological barriers, Brazil must promote R&D in battery technology, potentially through public-private partnerships. Strengthening local production capacity for batteries and other critical EV components can reduce reliance on international supply chains;
- Grid readiness and renewable energy integration: A strategic focus on modernizing Brazil’s electricity grid is essential to support the increased demand from EVs. Investments in smart grids, energy storage, and grid management systems, alongside policies to encourage renewable energy sources, are critical to ensure that EV growth does not compromise grid stability;
- Stakeholder collaboration: Collaboration between government, private companies, and civil society is necessary to address regulatory gaps, promote innovation, and foster infrastructure development. Multi-stakeholder platforms should be established to coordinate efforts and ensure that regulatory and market dynamics effectively evolve;

By addressing these barriers and drawing strategic implications, Brazil can develop a comprehensive roadmap to support the successful electrification of its light vehicle fleet by 2050, contributing to the decarbonisation of the transport sector and the achievement of broader environmental goals.

## 3.9. Final considerations

This chapter has presented a comprehensive conceptual framework for prospective scenario modelling, designed to assess the potential impacts of electrification on the decarbonisation of Brazil's LDV fleet. The proposed methodology integrates the Global Business Network (GBN) scenario planning approach with advanced analytical tools developed by the Laboratoire d'Investigation en Prospective, Stratégie et Organisation (Lipsor), particularly structural analysis and morphological matrices. This hybrid approach offers a foundation for exploring possible futures and their implications for Brazil's transportation sector.

The seven-step process outlined in this chapter provides a systematic method for scenario construction, from defining guiding questions to analyzing barriers and strategic implications. This structured approach ensures that the resulting scenarios are not only plausible and internally consistent but also relevant to the specific challenges and opportunities facing Brazil's LDV fleet.

The use of structural analysis, as can be demonstrated with support of the MICMAC software (Lipsor, 2024), allows for a nuanced understanding of the complex system dynamics at play. By identifying and classifying key variables based on their influence and dependence, this technique reveals the driving forces and critical uncertainties that will shape the future of vehicle electrification in Brazil. This deep understanding of system dynamics is crucial for developing scenarios that capture the full range of possible futures.

The incorporation of morphological analysis further enhances the scenario building process by enabling a systematic exploration of possible future configurations. This technique ensures that all potential combinations of key variables are considered, leading to a comprehensive set of scenarios that cover the full spectrum of possible outcomes.

A particularly valuable aspect of the proposed framework is its emphasis on stakeholder identification and analysis. By recognizing the diverse actors involved in the electrification of Brazil's light vehicle fleet – from government agencies and automotive manufacturers to consumers and environmental organizations – the framework ensures that the resulting scenarios account for the complex interplay of interests and influences that will shape the transition.

The framework's consideration of both near-term (2025-2030), medium-term (2031-2040), and long-term (2041-2050) trajectories is another strength. This dual-timeline approach allows for a more nuanced exploration of how initial policy decisions and market developments might evolve over time, providing valuable insights for both immediate action and long-term strategy.

Moreover, the inclusion of barrier analysis and strategic implications in the final step of the process ensures that the scenarios are not merely descriptive but also actionable. By identifying potential obstacles to electrification and suggesting strategies to overcome them, the framework provides practical value to policymakers, industry leaders, and other stakeholders.

It's important to note that while this framework provides a robust method for scenario construction, its effectiveness ultimately depends on the quality of inputs and the expertise of those applying it. The complex and rapidly evolving nature of vehicle electrification technology, energy markets, and climate policy means that ongoing refinement and updating of the scenarios will be necessary.

It's important to note that the practical application of this conceptual framework will be thoroughly demonstrated in the following chapter. This application will include visual representations that enhance understanding and illustrate the methodology's effectiveness. Specifically, Chapter 4 will represent graphically an influence/dependence map resulting from the structural analysis. This visual tool will clearly depict the relationships between key variables, highlighting those that are most critical in shaping the future scenarios of electrification of the LDV fleet in Brazil by 2050.

Furthermore, the next chapter will showcase five distinct morphological matrices, each corresponding to a different decarbonisation scenario for Brazil's LDV fleet. These matrices will provide a clear, visual representation of how different combinations of variable states come together to form coherent and plausible future scenarios. By presenting these visual tools, the next chapter will not only demonstrate the practical application of the framework but also offer readers a more intuitive grasp of the scenario-building process and its outcomes.

In conclusion, as Brazil moves forward on its path to a more sustainable transportation future, this framework, along with its practical application demonstrated in the next chapter, can serve as a crucial tool for navigating uncertainty and identifying effective strategies for change, making it more accessible and actionable for policymakers, industry leaders, and other stakeholders involved in shaping Brazil's automotive and energy future.

# 4
# Brazilian light vehicle fleet decarbonisation scenarios through electrification

This chapter presents five alternative decarbonisation scenarios for Brazil's light vehicle fleet through 2050, elucidating the complex interplay among policy frameworks, technological advancements, and societal factors that may influence the trajectory of fleet electrification during this period. These scenarios are constructed to encompass both near-term (2025–2035) and long-term (2036–2050) trajectories, offering a comprehensive analysis of how initial policy decisions and interventions could significantly shape the decarbonisation landscape of the light vehicle fleet by mid-century. The five scenarios span a spectrum from minimal to extensive electrification and decarbonisation, providing a prospective view of the potential evolution of the Brazilian LDV fleet composition and its consequent impact on GHG emissions.

## 4.1.
## Definition of the guiding questions and time horizon

The guiding question was defined in light of the research gaps identified during the literature review, while the time horizon for building the decarbonisation scenarios was established in line with the horizon of the National Energy Plan – PNE 2050 (MME, 2020) and the Paris Agreement to keep global temperatures under a 2˚C increase.

The guiding questions are: "To what extent can electrification enhance the decarbonisation of the light vehicle fleet in Brazil considering the 2050 time-horizon?".

## 4.2.
## Definition and classification of key variables: use of the structural analysis

To define and classify the key variables essential for constructing decarbonisation scenarios, structural analysis was applied. This method encompasses the following steps: (i) identification and description of key variables;

(ii) analysis of the relationships between the key variables, using the MICMAC computational tool (LIPSOR, 2024); (iii) classification of key variables according to the influence and dependence between them; (iv) drawing of the influence-dependence diagram resulting from the structural analysis; (v) structural analysis allows describing a system through the construction of a matrix that relates all the constituent elements of that system.

Structural analysis aims to explain the main influential and dependent variables, considered essential to the evolution of the system. In this study, two meetings were held with the participation of experts in this research field: the first for the identification and description of the key variables to be scenarized, and the second for the analysis of the relationships between the key variables, as described below.

As a result of the first meeting, a set of 14 key variables was defined, as presented in Table 4.1, with the two resultant variables at the bottom.

Table 4.1 – Key variables for building Brazilian light-duty vehicle fleet decarbonisation scenarios – horizon 2050

| Variable | Description |
|---|---|
| Light-duty EV policy support (EVPO) | Government policies that encourage the adoption of light-duty EVs. |
| Incentives for battery recycling/reuse (RECY) | Government and institutional measures to support the recycling and reuse of EV batteries. |
| Electricity price (ELEP) | The electricity supply, demand, and price influencing the attractiveness of EVs. |
| EV ownership costs (COST) | The total cost of owning and operating an EV, including purchase, maintenance, and charging. |
| Business model for light-duty PEVs (PLUG) | The business frameworks for buying and selling electricity through V2X technology. |
| Public preference towards light-duty EVs (PREF) | Societal attitudes and consumer preferences for EVs over ICE vehicles. |
| Skilled labour for EVs (SLAB) | The availability of a workforce trained to manufacture, maintain, and operate electric vehicles and charging infrastructure. |
| Vehicle autonomy for EVs (AUTO) | The range and operational autonomy of EVs measured by the distance that it can run before having to recharge or refuel. |
| Fuelling/Charging time (CHAR) | The time required to recharge an EV compared to refuelling an ICE vehicle. |
| Vehicle lifetime (LIFE) | The average operational lifespan of EVs compared to conventional vehicles. |
| Charging infrastructure deployment (INFR) | The development of public and private charging stations for EV users. |
| T&D network effectiveness to handle EV charging demands (T&D) | The efficiency of the transmission and distribution (T&D) network to handle EV charging demands. |
| EV share in LDV fleet (%) (EVSH) | The proportion of EVs in the country's LDV fleet. |
| Potential reduction of GHG emissions (%) (GHGE) | The potential reduction of GHG emissions through the electrification of the LDV fleet. |

From a systemic perspective, a variable exists only through the relationships it maintains with other variables. Structural analysis, therefore, aims to identify these relationships by employing a double-entry matrix known as the structural analysis matrix.

During the second structural analysis meeting, invited experts completed this matrix. For each pair of variables, the following question was posed: does a direct influence exist between variable i and variable j? If no direct influence was observed, a rating of 0 was assigned. If a direct influence was identified, it was further classified as weak (1), moderate (2), or strong (3).

Using the MICMAC computational tool (Lipsor, 2024), this process yielded a matrix of direct influences between the key variables (Figure 4.1).

| | 1 : EVPO | 2 : RECY | 3 : ELPR | 4 : COST | 5 : PLUG | 6 : PREF | 7 : SLAB | 8 : AUTO | 9 : CHAR | 10 : LIFE | 11 : INFR | 12 : TRDI | 13 : EVSH | 14 : GHGE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 : EVPO | 0 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | 0 | 3 | 3 | 3 | 3 |
| 2 : RECY | 1 | 0 | 2 | 3 | 2 | 1 | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 3 : ELPR | 0 | 0 | 0 | 3 | 2 | 3 | 2 | 0 | 0 | 0 | 1 | 1 | 3 | 3 |
| 4 : COST | 2 | 2 | 2 | 0 | 2 | 3 | 3 | 0 | 0 | 0 | 2 | 2 | 3 | 3 |
| 5 : PLUG | 1 | 3 | 3 | 2 | 0 | 3 | 3 | 0 | 0 | 0 | 2 | 2 | 3 | 3 |
| 6 : PREF | 3 | 3 | 3 | 3 | 3 | 0 | 3 | 0 | 0 | 0 | 2 | 2 | 3 | 3 |
| 7 : SLAB | 0 | 1 | 0 | 3 | 3 | 3 | 0 | 0 | 0 | 3 | 2 | 0 | 3 | 3 |
| 8 : AUTO | 0 | 0 | 0 | 2 | 2 | 3 | 0 | 0 | 0 | 2 | 2 | 2 | 3 | 3 |
| 9 : CHAR | 0 | 0 | 0 | 2 | 3 | 3 | 0 | 0 | 0 | 0 | 2 | 3 | 3 | 3 |
| 10 : LIFE | 1 | 1 | 1 | 2 | 2 | 3 | 0 | 3 | 1 | 0 | 1 | 1 | 1 | 2 |
| 11 : INFR | 1 | 1 | 3 | 3 | 3 | 3 | 2 | 1 | 1 | 0 | 0 | 3 | 3 | 3 |
| 12 : TRDI | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 0 | 1 | 0 | 2 | 0 | 2 | 2 |
| 13 : EVSH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 14 : GHGE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |



Figure 4.1 – Matrix of direct influence (MDI) of key variables

To assess the indirect influences, the matrix was multiplied by itself successively until the ranking of the variables stabilized (Figure 4.2).

| | 1 : EVPO | 2 : RECY | 3 : ELPR | 4 : COST | 5 : PLUG | 6 : PREF | 7 : SLAB | 8 : AUTO | 9 : CHAR | 10 : LIFE | 11 : INFR | 12 : TRDI | 13 : EVSH | 14 : GHGE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 : EVPO | 497 | 748 | 827 | 975 | 942 | 1014 | 908 | 133 | 149 | 144 | 695 | 681 | 1177 | 1442 |
| 2 : RECY | 234 | 339 | 391 | 489 | 466 | 470 | 418 | 65 | 70 | 82 | 315 | 323 | 554 | 687 |
| 3 : ELPR | 223 | 352 | 402 | 527 | 490 | 520 | 449 | 78 | 85 | 83 | 337 | 339 | 586 | 723 |
| 4 : COST | 348 | 514 | 578 | 702 | 685 | 760 | 646 | 89 | 97 | 117 | 501 | 501 | 859 | 1042 |
| 5 : PLUG | 346 | 536 | 582 | 691 | 666 | 753 | 651 | 93 | 100 | 116 | 510 | 497 | 855 | 1036 |
| 6 : PREF | 429 | 614 | 687 | 848 | 829 | 864 | 751 | 93 | 108 | 151 | 594 | 583 | 1020 | 1236 |
| 7 : SLAB | 269 | 431 | 474 | 646 | 617 | 649 | 549 | 69 | 97 | 121 | 447 | 422 | 751 | 891 |
| 8 : AUTO | 230 | 369 | 415 | 566 | 532 | 566 | 481 | 62 | 84 | 97 | 380 | 375 | 650 | 776 |
| 9 : CHAR | 228 | 364 | 416 | 581 | 542 | 566 | 485 | 64 | 86 | 97 | 369 | 364 | 647 | 785 |
| 10 : LIFE | 300 | 459 | 516 | 623 | 605 | 645 | 559 | 82 | 101 | 99 | 434 | 423 | 741 | 907 |
| 11 : INFR | 387 | 575 | 658 | 803 | 769 | 803 | 715 | 106 | 120 | 127 | 534 | 546 | 934 | 1151 |
| 12 : TRDI | 267 | 407 | 441 | 533 | 527 | 573 | 495 | 56 | 76 | 98 | 397 | 366 | 663 | 800 |
| 13 : EVSH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 : GHGE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |



Figure 4.2 – Matrix of indirect influence (MII) of key variables

The comparison of the hierarchy of variables in the different classifications (direct and indirect) revealed key variables that, due to their indirect influence on others, play a predominant role not perceived in the direct classification. Thus, by structural analysis, the classification of the 14 key variables was reached, according to their degree of influence and dependence.

The influence- dependence map presented in Figure 4.3 refers to the matrix of indirect influence (MII).

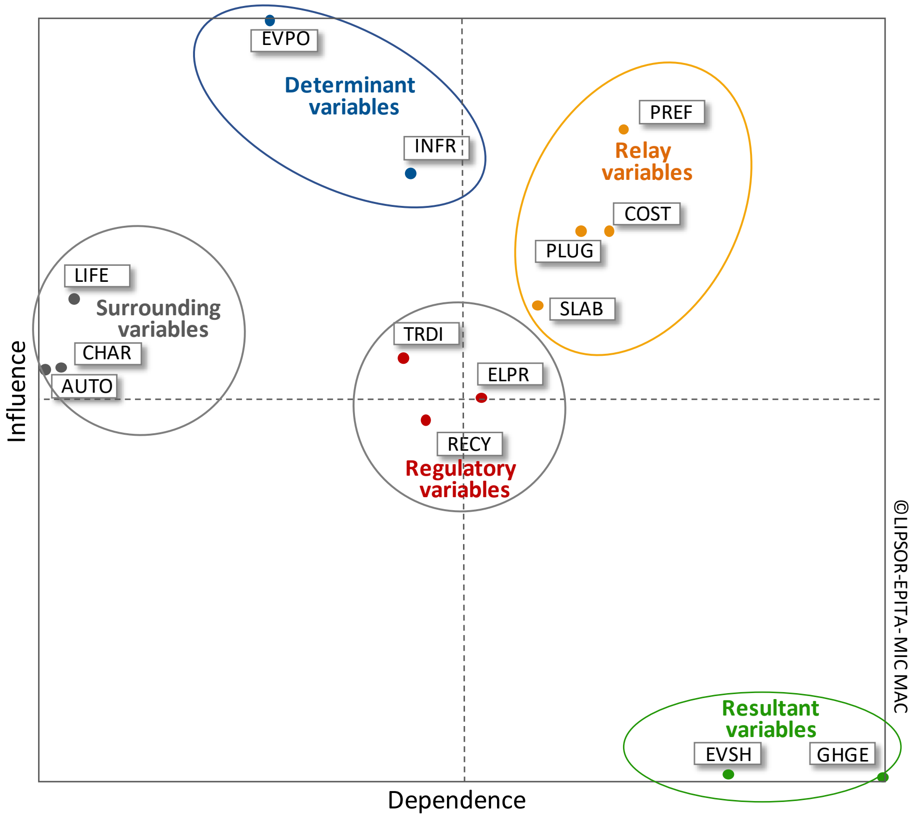


Figure 4.3 – Indirect influence/dependence map

**Notation:**
AUTO – Vehicle autonomy for EVs
CHAR – Fuelling/Charging time
COST– EVs ownership costs
ELEP – Electricity price
EVPO – Light EV policy support
EVSH – EV share in light-duty vehicle fleet (%)
GHGE – Potential reduction of GHG emissions (%)
INFR – Charging infrastructure deployment
LIFE – Vehicle lifetime
PLUG – Business model for plug-in light EVs
PREF – Public preference towards light EVs
RECY – Incentives for battery recycling/reuse
SLAB – Skilled labour for EVs
TRDI – T&D network effectiveness to handle EV charging demands

As can be seen in Figure 4.3, the variables were grouped and classified into five categories: (i) determinant variables or driving forces; (ii) surrounding variables; (iii) relay variables; (iv) regulatory variables; and (v) resultant variables.

Determinant variables or driving forces are located in the upper left quadrant of the influence-dependence map. They are the most relevant variables to explain the evolution of the issue object of the scenario together with the analysis of the conditions of the future associated with them, namely:

- EVPO – Light EV policy support;
- INFR – Charging infrastructure deployment.

The surrounding variables are located in the upper left quadrant of the influence-dependence map, just below the set of determinant variables. They refer to relevant issues complementary to the determining variables:

- LIFE – Vehicle lifetime;
- CHAR – Fuelling/Charging time;
- AUTO – Vehicle autonomy for EVs.

The relay variables are located in the upper right quadrant and are highly influential and highly dependent variables. They refer to:

- COST– EVs ownership costs;
- PLUG – Business model for plug-in light EVs;
- PREF – Public preference towards light EVs;
- SLAB – Skilled labour for EVs.

The regulatory variables located in the central area of the influence-dependence map play a regulatory role in the evolution of the resultant variables. The term “regulatory variables” is widely used in studies based on the theory of dynamic systems and refers to those variables that play a regulatory role in the evolution of the outcome variables of a given system. This term should not be confused with the term usually used to regulate productive activities. They are:

- TRDI – T&D network effectiveness to handle EV charging demands;
- RECY – Incentives for battery recycling/reuse;
- ELEP – Electricity price.

The resultant variables are located in the lower right quadrant and are:

- EVSH – EV share in light-duty vehicle fleet (%);
- GHGE – Potential reduction of GHG emissions (%).

## 4.3. Identification of key stakeholders and influencers of the scenarios

Key actors that will influence the future of the electrification of LDV fleet in Brazil are presented in Table 4.2. These actors will play determinant roles in shaping the future electrification of the LDV fleet in Brazil, influencing key variables such as EV adoption rates, infrastructure development, and overall emissions reduction.

Table 4.2 – Key actors in shaping the future of light vehicle fleet decarbonisation in Brazil – horizon 2050

| **Actor** | **Role** |
|---|---|
| Government and policymakers | Developing and implementing policies to support electrification, including incentives for EVs, regulations for ICE phase-out, and policies for ethanol use. |
| National Electric Energy Agency (ANEEL) | Ensuring fair pricing and distribution of electricity for EV charging |
| National Petroleum, Natural Gas and Biofuels Agency (ANP) | Regulating and incentivising the use of biofuels such as ethanol and eventually green hydrogen. Moreover, it can support the creation of a sustainable energy infrastructure that complements the electrification and decarbonization of the transport sector |
| Automotive manufacturers | Developing and producing EVs, HEVs, and PHEVs, as well as improving ICE efficiency. |
| Energy companies | Developing and maintaining the electricity grid, ensuring its capacity to handle increased EV charging demands. |
| Ethanol producers | Continuing to produce and innovate in ethanol production, particularly important for hybrid Flex vehicles. |
| Battery manufacturers | Developing more efficient and sustainable batteries, crucial for improving EV performance and reducing costs. |
| Charging infrastructure providers | Expanding and maintaining the network of charging stations |
| Consumers | Adopting new vehicle technologies and influencing market demand. |
| Environmental organizations | Advocating for stricter emissions standards and promoting sustainable transportation. |
| Research institutions and universities | Conducting research on new technologies and providing data for policy decisions. |
| Financial Institutions | Providing financing options for EV purchases and infrastructure development. |
| Oil companies | Adapting business models to the changing energy landscape in transportation |
| Public transportation authorities | Integrating EVs into public transport systems |
| Urban planners | Designing cities to accommodate increased EV use and charging infrastructure. |
| Recycling and waste management companies | As the EV market grows, these companies will play an increasingly important role in managing end-of-life batteries and vehicles, contributing to the circular economy aspects of EV adoption |

## 4.4. Characterization of the current situation (2024) and future determinants

Brazil's LDV fleet in 2024 remains overwhelmingly dominated by ICE vehicles, which make up 99.52% of the total fleet. EVs, including HEVs, PHEVs, and BEVs, collectively account for less than 0.5% of the fleet. The current low electrification rate is the result of an interplay of factors. Brazil's automotive industry, has been slow to pivot towards electrification. The country's unique position as a major ethanol producer has also played a role, providing a partial alternative to gasoline and contributing to energy independence, but potentially slowing the urgency for full electrification. Moreover, the high upfront costs of EVs have put them out of reach for many Brazilian consumers, while the limited charging infrastructure, particularly outside urban centres, has fuelled range anxiety among potential buyers.

Government policies have yet to provide strong incentives for EV adoption, and public awareness of the benefits of electric mobility remains limited. The cultural attachment to traditional vehicles, combined with a lack of diverse EV options in the market, has further stifled the transition.

Looking ahead to 2050, the path of Brazil's LDV fleet electrification is poised for significant change, shaped by a myriad of interconnected future determinants, such as major trends, invariants, and critical uncertainties, as follows:

- Trends: EV technology advancements; gradual shift in consumer preferences towards EVs as environmental concerns grow and EV performance improves; increasing international pressure to reduce transportation sector emissions, influencing domestic policy; and shifts in urban planning and personal mobility preferences, potentially favouring electric and shared mobility solutions.
- Critical uncertainties: Government policy and regulation; charging infrastructure development; electricity grid modernization; evolution of EV prices relative to ICE vehicles and development of new financing models for EV purchases; domestic EV manufacturing capacity; and recycling and reuse of EV batteries;
- Invariant or major trend: Continued importance of ethanol in Brazil's fuel mix, potentially integrated with electrification through flex-fuel hybrid vehicles.

Government policy will play a crucial role, with the potential implementation of ICE phase-out timelines and comprehensive EV incentive programs potentially accelerating the transition. The development of charging infrastructure, particularly along highways and in rural areas, will be vital in alleviating range anxiety and making EVs a viable option for more Brazilians.

Technological advancements are expected to drive improvements in EV performance and affordability. Battery technology will likely see substantial progress, increasing vehicle range and reducing costs. These advancements, coupled with the expansion of fast-charging capabilities, could make EVs increasingly attractive to consumers.

The modernization of Brazil's electricity grid will be a critical factor. Upgrades to T&D networks will be necessary to handle the increased demand from EV charging, while the integration of renewable energy sources will be crucial in maintaining the environmental benefits of electrification.

Economic factors will continue to play a significant role. The evolution of EV prices relative to ICE vehicles, along with new financing models, could make electric vehicles more accessible to a broader range of consumers. As the total cost of ownership for EVs potentially decreases, it could tip the scales in favour of electrification.

Public perception and awareness are expected to shift gradually. As environmental concerns grow and EV performance improves, consumer preferences may increasingly lean towards electric options. The increased visibility of EVs on roads and a wider range of available models could further normalize electric mobility in the public consciousness.

The development of domestic EV manufacturing capacity will be a key determinant. The transition of Brazil's robust automotive industry towards EV technologies could not only accelerate adoption but also provide economic benefits and job creation. Interestingly, Brazil's strong ethanol industry is likely to remain a significant factor. The country may chart a unique path, potentially integrating ethanol production with electrification through technologies like flex-fuel hybrid vehicles.

Global climate policy will exert increasing pressure on Brazil to reduce emissions in its transportation sector, likely influencing domestic policy decisions.

Simultaneously, changing urbanization patterns and evolving mobility preferences could favour electric and shared mobility solutions, particularly in major cities.

The recycling and reuse of EV batteries emerge as a critical uncertainty in Brazil's electrification journey towards 2050. As the EV fleet grows, the country will face increasing volumes of end-of-life batteries, presenting both challenges and opportunities. The development of efficient, large-scale battery recycling infrastructure will be crucial for environmental sustainability and resource conservation. However, the path to establishing this infrastructure is uncertain, dependent on technological advancements, economic feasibility, and supportive policies.

Moreover, the potential for second-life applications of EV batteries could significantly impact the overall sustainability and economics of electric mobility. These batteries, while no longer suitable for vehicular use, often retain substantial capacity for less demanding applications such as stationary energy storage. The extent to which Brazil can develop markets and applications for these second-life batteries remains uncertain. Success in this area could enhance the economic proposition of EVs by providing additional value at the end of the battery's first life, while also supporting the integration of renewable energy into the grid. However, the realization of this potential will depend on the development of standardized processes for battery assessment and repurposing, as well as the creation of regulatory frameworks to govern the use of second-life batteries. The effectiveness of incentives for battery recycling and reuse (RECY), as highlighted in the scenarios, will play a crucial role in determining the outcome of this critical uncertainty.

As these various factors intertwine and evolve over the coming decades, they will shape the electrification journey of Brazil's light vehicle fleet. While the road to 2050 is filled with both challenges and opportunities, it's clear that Brazil's automotive landscape is on the cusp of a significant transformation, with the potential for a much greener, more electrified future on the horizon.

## 4.5
## Construction of prospective scenarios: use of morphological matrices

To evaluate the extent to which electrification can enhance the Brazilian light vehicle fleet decarbonisation, five scenarios were built for the 2050 horizon were built using GMA (Zwicky, 1969; Godet, 2000). They are: (i) Scenario A – “Low decarbonisation with low electrification”; (ii) Scenario B – “Moderate decarbonisation with low electrification”; (iii) Scenario C – “High decarbonisation with moderate electrification”; (iv) Scenario D – “High decarbonisation with moderate electrification plus ethanol"; and (v) Scenario E – "High decarbonisation with high electrification".

By employing the cross-consistency assessment technique (Zwicky, 1969; Godet, 2000), a comprehensive morphological matrix was constructed, incorporating 14 key variables as delineated in Table 4.1, supplemented by three exogenous variables: the phaseout of internal combustion engine sales (ICES), incentive policies for ethanol production and consumption (ETHA), and incentive policies aimed at promoting a cleaner electricity matrix (MATR).

The five scenarios align with the colour-coded hypotheses in the morphological matrices (Figures 4.4 to 4.8).

| Scenario A – Low decarbonisation with low electrification | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Hypothesis** | | | | |
| ICE sales phaseout (ICES) | No phaseout | Starting in 2045 | Starting in 2040 | | |
| Incentive policies for ethanol (ETHA) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Incentive policies for cleaner electricity matrix (MATR) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Light-duty EV policy support (EVPO) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Incentives for battery recycling/reuse (RECY) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Electricity price (ELEP) | Very high-level price | High-level price | Middle-level price | Low-level price | Very low-level price |
| EV ownership costs (COST) | Very high-level price | High-level price | Middle-level price | Low-level price | Very low-level price |
| Business model for light-duty PEVs (PLUG) | G2V | V2B | V2X | | |
| Public preference towards light-duty EVs (PREF) | Strong resistance to light EVs | Slight resistance to light EVs | Neutral stance towards light EVs | Slight preference for light EVs | Strong preference for light EVs |
| Skilled labour for EVs (SLAB) | Severe shortage of skilled EV workers | Shortage of skilled EV workers | Adequate supply of skilled EV workers | | |
| Vehicle autonomy for EVs (AUTO) | Low autonomy | Moderate autonomy | High autonomy | | |
| Fuelling/Charging time (CHAR) | 1 hour for 80% charge | 30 min for 80% charge | <15 min for 80% charge | | |
| Vehicle lifetime (LIFE) | 5-10 years | >10-15 years | >15 years | | |
| Charging infrastructure deployment (INFR) | Minimal charging stations, mostly in urban areas | Limited charging stations, mainly in cities and major highways | Adequate charging stations in cities and highways | | |
| T&D network effectiveness to handle EV charging demands (T&D) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| EV share in light-duty vehicle fleet (%) (EVSH) | ICE: 67.0<br>HEV: 10.0<br>HEV Flex: 10.0<br>PHEV: 8.0<br>BEV: 5.0 | ICE: 61.0<br>HEV: 10.00<br>HEV Flex: 12.0<br>PHEV: 10.0<br>BEV: 7.0 | ICE: 50.0<br>HEV: 16.0<br>HEV Flex: 8.0<br>PHEV: 10.0<br>BEV: 16.0 | ICE: 50.0<br>HEV: 8.00<br>HEV Flex: 16.0<br>PHEV: 10.0<br>BEV: 16.0 | ICE: 50.0<br>HEV: 2.0<br>HEV Flex: 6.0<br>PHEV: 12.00<br>BEV: 30.0 |
| Potential reduction of GHG emissions (%) (GHGE) | 7 | 8.8 | 12.8 | 21.3 | 25.7 |

Figure 4.4 – Morphological matrix for building Scenario A “Low decarbonisation with low electrification”: 2050 horizon

| Scenario B – Moderate decarbonisation with low electrification | | | | | |
|---|---|---|---|---|---|
| **Variable** | **Hypothesis** | | | | |
| ICE sales phaseout (ICES) | No phaseout | Starting in 2045 | Starting in 2040 | | |
| Incentive policies for ethanol (ETHA) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Incentive policies for cleaner electricity matrix (MATR) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Light-duty EV policy support (EVPO) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Incentives for battery recycling/reuse (RECY) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| Electricity price (ELEP) | Very high-level price | High-level price | Middle-level price | Low-level price | Very low-level price |
| EV ownership costs (COST) | Very high-level price | High-level price | Middle-level price | Low-level price | Very low-level price |
| Business model for light-duty PEVs (PLUG) | G2V | V2B | V2X | | |
| Public preference towards light-duty EVs (PREF) | Strong resistance to light EVs | Slight resistance to light EVs | Neutral stance towards light EVs | Slight preference for light EVs | Strong preference for light EVs |
| Skilled labour for EVs (SLAB) | Severe shortage of skilled EV workers | Shortage of skilled EV workers | Adequate supply of skilled EV workers | | |
| Vehicle autonomy for EVs (AUTO) | Low autonomy | Moderate autonomy | High autonomy | | |
| Fuelling/Charging time (CHAR) | 1 hour for 80% charge | 30 min for 80% charge | <15 min for 80% charge | | |
| Vehicle lifetime (LIFE) | 5-10 years | >10-15 years | >15 years | | |
| Charging infrastructure deployment (INFR) | Minimal charging stations, mostly in urban areas | Limited charging stations, mainly in cities and major highways | Adequate charging stations in cities and highways | | |
| T&D network effectiveness to handle EV charging demands (T&D) | Low effectiveness | Moderate effectiveness | High effectiveness | | |
| EV share in light-duty vehicle fleet (%) (EVSH) | ICE: 67.0<br>HEV: 10.0<br>HEV Flex: 10.0<br>PHEV: 8.0<br>BEV: 5.0 | ICE: 61.0<br>HEV: 10.00<br>HEV Flex: 12.0<br>PHEV: 10.0<br>BEV: 7.0 | ICE: 50.0<br>HEV: 16.0<br>HEV Flex: 8.0<br>PHEV: 10.0<br>BEV: 16.0 | ICE: 50.0<br>HEV: 8.00<br>HEV Flex: 16.0<br>PHEV: 10.0<br>BEV: 16.0 | ICE: 50.0<br>HEV: 2.0<br>HEV Flex: 6.0<br>PHEV: 12.00<br>BEV: 30.0 |
| Potential reduction of GHG emissions (%) (GHGE) | 7 | 8.8 | 12.8 | 21.3 | 25.7 |

Figure 4.5 – Morphological matrix for building Scenario B “Moderate decarbonisation with low electrification”: 2050 horizon

<table>
<tr><th colspan="16">Scenario C – High decarbonisation with moderate electrification</th></tr>
<tr><th>Variable</th><th colspan="15">Hypothesis</th></tr>
<tr><td>ICE sales phaseout (ICES)</td><td colspan="5">No phaseout</td><td colspan="5">Starting in 2045</td><td colspan="5">Starting in 2040</td></tr>
<tr><td>Incentive policies for ethanol (ETHA)</td><td colspan="5">Low effectiveness</td><td colspan="5">Moderate effectiveness</td><td colspan="5">High effectiveness</td></tr>
<tr><td>Incentive policies for cleaner electricity matrix (MATR)</td><td colspan="5">Low effectiveness</td><td colspan="5">Moderate effectiveness</td><td colspan="5">High effectiveness</td></tr>
<tr><td>Light-duty EV policy support (EVPO)</td><td colspan="5">Low effectiveness</td><td colspan="5">Moderate effectiveness</td><td colspan="5">High effectiveness</td></tr>
<tr><td>Incentives for battery recycling/reuse (RECY)</td><td colspan="5">Low effectiveness</td><td colspan="5">Moderate effectiveness</td><td colspan="5">High effectiveness</td></tr>
<tr><td>Electricity price (ELEP)</td><td colspan="3">Very high-level price</td><td colspan="3">High-level price</td><td colspan="3">Middle-level price</td><td colspan="3">Low-level price</td><td colspan="3">Very low-level price</td></tr>
<tr><td>EV ownership costs (COST)</td><td colspan="3">Very high-level price</td><td colspan="3">High-level price</td><td colspan="3">Middle-level price</td><td colspan="3">Low-level price</td><td colspan="3">Very low-level price</td></tr>
<tr><td>Business model for light-duty PEVs (PLUG)</td><td colspan="5">G2V</td><td colspan="5">V2B</td><td colspan="5">V2X</td></tr>
<tr><td>Public preference towards light-duty EVs (PREF)</td><td colspan="3">Strong resistance to light EVs</td><td colspan="3">Slight resistance to light EVs</td><td colspan="3">Neutral stance towards light EVs</td><td colspan="3">Slight preference for light EVs</td><td colspan="3">Strong preference for light EVs</td></tr>
<tr><td>Skilled labour for EVs (SLAB)</td><td colspan="5">Severe shortage of skilled EV workers</td><td colspan="5">Shortage of skilled EV workers</td><td colspan="5">Adequate supply of skilled EV workers</td></tr>
<tr><td>Vehicle autonomy for EVs (AUTO)</td><td colspan="5">Low autonomy</td><td colspan="5">Moderate autonomy</td><td colspan="5">High autonomy</td></tr>
<tr><td>Fuelling/Charging time (CHAR)</td><td colspan="5">1 hour for 80% charge</td><td colspan="5">30 min for 80% charge</td><td colspan="5"><15 min for 80% charge</td></tr>
<tr><td>Vehicle lifetime (LIFE)</td><td colspan="5">5-10 years</td><td colspan="5">>10-15 years</td><td colspan="5">>15 years</td></tr>
<tr><td>Charging infrastructure deployment (INFR)</td><td colspan="5">Minimal charging stations, mostly in urban areas</td><td colspan="5">Limited charging stations, mainly in cities and major highways</td><td colspan="5">Adequate charging stations in cities and highways</td></tr>
<tr><td>T&D network effectiveness to handle EV charging demands (T&D)</td><td colspan="5">Low effectiveness</td><td colspan="5">Moderate effectiveness</td><td colspan="5">High effectiveness</td></tr>
<tr><td>EV share in light-duty vehicle fleet (%) (EVSH)</td><td colspan="3">ICE: 67.0<br>HEV: 10.0<br>HEV Flex: 10.0<br>PHEV: 8.0<br>BEV: 5.0</td><td colspan="3">ICE: 61.0<br>HEV: 10.00<br>HEV Flex: 12.0<br>PHEV: 10.0<br>BEV: 7.0</td><td colspan="3">ICE: 50.0<br>HEV: 16.0<br>HEV Flex: 8.0<br>PHEV: 10.0<br>BEV: 16.0</td><td colspan="3">ICE: 50.0<br>HEV: 8.00<br>HEV Flex: 16.0<br>PHEV: 10.0<br>BEV: 16.0</td><td colspan="3">ICE: 50.0<br>HEV: 2.0<br>HEV Flex: 6.0<br>PHEV: 12.00<br>BEV: 30.0</td></tr>
<tr><td>Potential reduction of GHG emissions (%) (GHGE)</td><td colspan="3">7</td><td colspan="3">8.8</td><td colspan="3">12.8</td><td colspan="3">21.3</td><td colspan="3">25.7</td></tr>
</table>

Figure 4.6 – Morphological matrix for building Scenario C “High decarbonisation with moderate electrification”: 2050 horizon

<table>
<tr><th colspan="8">Scenario D – High decarbonisation with moderate electrification plus ethanol</th></tr>
<tr><th>Variable</th><th colspan="7">Hypothesis</th></tr>
<tr><td>ICE sales phaseout (ICES)</td><td colspan="2">No phaseout</td><td colspan="3">Starting in 2045</td><td colspan="2">Starting in 2040</td></tr>
<tr><td>Incentive policies for ethanol (ETHA)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Incentive policies for cleaner electricity matrix (MATR)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Light-duty EV policy support (EVPO)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Incentives for battery recycling/reuse (RECY)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Electricity price (ELEP)</td><td>Very high-level price</td><td colspan="2">High-level price</td><td>Middle-level price</td><td colspan="2">Low-level price</td><td>Very low-level price</td></tr>
<tr><td>EV ownership costs (COST)</td><td>Very high-level price</td><td colspan="2">High-level price</td><td>Middle-level price</td><td colspan="2">Low-level price</td><td>Very low-level price</td></tr>
<tr><td>Business model for light-duty PEVs (PLUG)</td><td colspan="2">G2V</td><td colspan="3">V2B</td><td colspan="2">V2X</td></tr>
<tr><td>Public preference towards light-duty EVs (PREF)</td><td>Strong resistance to light EVs</td><td colspan="2">Slight resistance to light EVs</td><td>Neutral stance towards light EVs</td><td colspan="2">Slight preference for light EVs</td><td>Strong preference for light EVs</td></tr>
<tr><td>Skilled labour for EVs (SLAB)</td><td colspan="2">Severe shortage of skilled EV workers</td><td colspan="3">Shortage of skilled EV workers</td><td colspan="2">Adequate supply of skilled EV workers</td></tr>
<tr><td>Vehicle autonomy for EVs (AUTO)</td><td colspan="2">Low autonomy</td><td colspan="3">Moderate autonomy</td><td colspan="2">High autonomy</td></tr>
<tr><td>Fuelling/Charging time (CHAR)</td><td colspan="2">1 hour for 80% charge</td><td colspan="3">30 min for 80% charge</td><td colspan="2"><15 min for 80% charge</td></tr>
<tr><td>Vehicle lifetime (LIFE)</td><td colspan="2">5-10 years</td><td colspan="3">>10-15 years</td><td colspan="2">>15 years</td></tr>
<tr><td>Charging infrastructure deployment (INFR)</td><td colspan="2">Minimal charging stations, mostly in urban areas</td><td colspan="3">Limited charging stations, mainly in cities and major highways</td><td colspan="2">Adequate charging stations in cities and highways</td></tr>
<tr><td>T&D network effectiveness to handle EV charging demands (T&D)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>EV share in light-duty vehicle fleet (%) (EVSH)</td><td>ICE: 67.0<br>HEV: 10.0<br>HEV Flex: 10.0<br>PHEV: 8.0<br>BEV: 5.0</td><td colspan="2">ICE: 61.0<br>HEV: 10.00<br>HEV Flex: 12.0<br>PHEV: 10.0<br>BEV: 7.0</td><td>ICE: 50.0<br>HEV: 16.0<br>HEV Flex: 8.0<br>PHEV: 10.0<br>BEV: 16.0</td><td colspan="2">ICE: 50.0<br>HEV: 8.00<br>HEV Flex: 16.0<br>PHEV: 10.0<br>BEV: 16.0</td><td>ICE: 50.0<br>HEV: 2.0<br>HEV Flex: 6.0<br>PHEV: 12.00<br>BEV: 30.0</td></tr>
<tr><td>Potential reduction of GHG emissions (%) (GHGE)</td><td>7</td><td colspan="2">8.8</td><td>12.8</td><td colspan="2">21.3</td><td>25.7</td></tr>
</table>

Figure 4.7 – Morphological matrix for building Scenario D “High decarbonisation with moderate electrification plus ethanol”: 2050 horizon

<table>
<tr><th colspan="8">Scenario E – High Decarbonisation with High Electrification</th></tr>
<tr><th>Variable</th><th colspan="7">Hypothesis</th></tr>
<tr><td>ICE sales phaseout (ICES)</td><td colspan="2">No phaseout</td><td colspan="3">Starting in 2045</td><td colspan="2">Starting in 2040</td></tr>
<tr><td>Incentive policies for ethanol (ETHA)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Incentive policies for cleaner electricity matrix (MATR)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Light-duty EV policy support (EVPO)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Incentives for battery recycling/reuse (RECY)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>Electricity price (ELEP)</td><td>Very high-level price</td><td colspan="2">High-level price</td><td>Middle-level price</td><td colspan="2">Low-level price</td><td>Very low-level price</td></tr>
<tr><td>EV ownership costs (COST)</td><td>Very high-level price</td><td colspan="2">High-level price</td><td>Middle-level price</td><td colspan="2">Low-level price</td><td>Very low-level price</td></tr>
<tr><td>Business model for light-duty PEVs (PLUG)</td><td colspan="2">G2V</td><td colspan="3">V2B</td><td colspan="2">V2X</td></tr>
<tr><td>Public preference towards light-duty EVs (PREF)</td><td>Strong resistance to light EVs</td><td colspan="2">Slight resistance to light EVs</td><td>Neutral stance towards light EVs</td><td colspan="2">Slight preference for light EVs</td><td>Strong preference for light EVs</td></tr>
<tr><td>Skilled labour for EVs (SLAB)</td><td colspan="2">Severe shortage of skilled EV workers</td><td colspan="3">Shortage of skilled EV workers</td><td colspan="2">Adequate supply of skilled EV workers</td></tr>
<tr><td>Vehicle autonomy for EVs (AUTO)</td><td colspan="2">Low autonomy</td><td colspan="3">Moderate autonomy</td><td colspan="2">High autonomy</td></tr>
<tr><td>Fuelling/Charging time (CHAR)</td><td colspan="2">1 hour for 80% charge</td><td colspan="3">30 min for 80% charge</td><td colspan="2"><15 min for 80% charge</td></tr>
<tr><td>Vehicle lifetime (LIFE)</td><td colspan="2">5-10 years</td><td colspan="3">>10-15 years</td><td colspan="2">>15 years</td></tr>
<tr><td>Charging infrastructure deployment (INFR)</td><td colspan="2">Minimal charging stations, mostly in urban areas</td><td colspan="3">Limited charging stations, mainly in cities and major highways</td><td colspan="2">Adequate charging stations in cities and highways</td></tr>
<tr><td>T&D network effectiveness to handle EV charging demands (T&D)</td><td colspan="2">Low effectiveness</td><td colspan="3">Moderate effectiveness</td><td colspan="2">High effectiveness</td></tr>
<tr><td>EV share in light-duty vehicle fleet (%) (EVSH)</td><td>ICE: 67.0<br>HEV: 10.0<br>HEV Flex: 10.0<br>PHEV: 8.0<br>BEV: 5.0</td><td colspan="2">ICE: 61.0<br>HEV: 10.00<br>HEV Flex: 12.0<br>PHEV: 10.0<br>BEV: 7.0</td><td>ICE: 50.0<br>HEV: 16.0<br>HEV Flex: 8.0<br>PHEV: 10.0<br>BEV: 16.0</td><td colspan="2">ICE: 50.0<br>HEV: 8.00<br>HEV Flex: 16.0<br>PHEV: 10.0<br>BEV: 16.0</td><td>ICE: 50.0<br>HEV: 2.0<br>HEV Flex: 6.0<br>PHEV: 12.00<br>BEV: 30.0</td></tr>
<tr><td>Potential reduction of GHG emissions (%) (GHGE)</td><td>7</td><td colspan="2">8.8</td><td>12.8</td><td colspan="2">21.3</td><td>25.7</td></tr>
</table>

Figure 4.8 – Morphological matrix for building Scenario E “High Decarbonisation with High Electrification”: 2050 horizon

## 4.6.
## Estimating the size of the light vehicle fleet and the potential reduction of GHG emissions

The size of the fleet was calculated by following the steps described in Section 3.6. The history of the circulating fleet was obtained from ANFAVEA (2024). The GDP was based on the "Superior" scenario on PNE 2050 by MME/EPE (2020), which projects 3.1% annual growth. Population growth was based on the projection by IBGE (2024). Table 4.3 shows the statistical parameters resulting from the linear regression analysis performed on MS Excel. The intercept was set to 0, as it resulted in a negative value in the first attempt. Figure 4.9 illustrates the projection of the fleet. The projected fleet is also aligned with the projection by EPE (2023b), which projects the LDV fleet up to 2034, with 50 million vehicles. This study's projection estimates around 56 million LDVs in 2034, but also accounts LCVs (Light Commercial Vehicles), which currently account for more than 5 million vehicles.

Table 4.3 - Linear regression statistical parameters

| **Statistical parameters** | **Calculated values** | | |
|---|---|---|---|
| Confidence level | 95% | | |
| Equation coefficients: $F(t) = \hat{a}(P(t)) + \hat{b}(GDP(t)) + \hat{c}$ | $\hat{a}$ = 0,1036 | $\hat{b}$ = 6,457 | $\hat{c} = 0$ |
| Standard error (SE) | $3.026 \times 10^6$ | | |
| $R^2$ | 0.9963 | | |
| F-statistic and degrees of freedom | 3204 | 26 | |
| Sum of squares | $6{,}61 \times 10^{16}$ | | |
| t-statistic for parameters $\hat{a}$ and $\hat{b}$ | 14,96 | 24,81 | |

The current LDV fleet was obtained from the annual estimation of the circulating fleet by, by adding the "Vehicles" and "Light commercials" categories. The ICE fleet was calculated by subtracting the electrified LDV fleet, provided by ABVE (2024a), from the total LDV fleet. ABVE's fleet accumulates sales since 2012, which is when records for EV sales started. The remaining EV categories were calculated by accumulating the yearly sales in each category. Table 4.4 shows the current category shares. The projection of the future fleets, explained in Section 3.6, was based on this starting point.

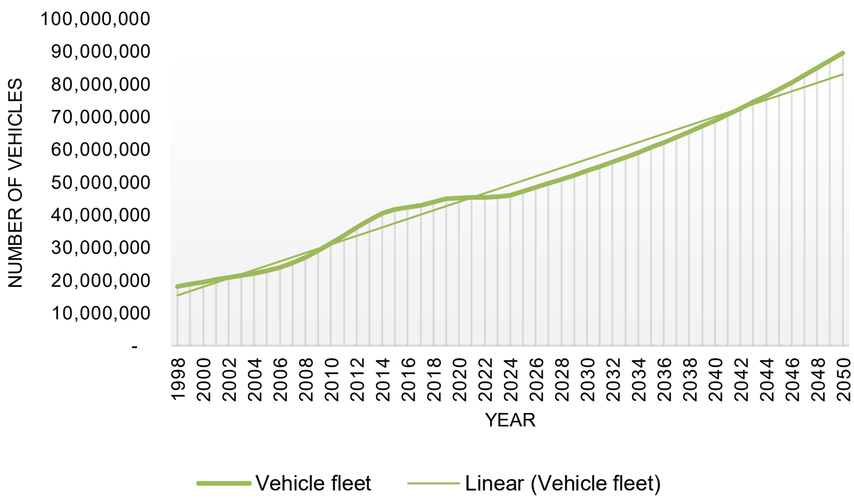


Figure 4.9 – LDV fleet projection

Table 4.4 – Light vehicle fleet share: current situation (2024)

| Vehicle category | 2024 fleet size | Share (%) | References |
|---|---|---|---|
| ICE | 45,439,495 | 99.52 | ANFAVEA (2024); ABVE (2024a) |
| HEV | 51,323 | 0.11 | ABVE (2024a); ABVE (2024b); ABVE (2024c), ABVE (2023) |
| HEV Flex | 82,477 | 0.18 | ABVE (2024a); ABVE (2024b); ABVE (2024c), ABVE (2023) |
| PHEV | 45,875 | 0.10 | ABVE (2024a); ABVE (2024b); ABVE (2024c), ABVE (2023) |
| BEV | 40,756 | 0.09 | ABVE (2024a); ABVE (2024b); ABVE (2024c), ABVE (2023) |
| **Total** | **45,659,926** | | ANFAVEA (2024); MME (2020); IBGE (2024) |

**Notation:**
ICE – Internal Combustion Engine vehicles: These are vehicles powered by engines that burn fuel (such as gasoline or diesel) to generate power.
HEV – Hybrid Electric Vehicles: These vehicles use both an internal combustion engine and an electric motor, powered by a battery, to improve fuel efficiency.
HEV flex – Hybrid Electric Vehicles (Flex): These are hybrid electric vehicles that can run on more than one type of fuel, such as gasoline and ethanol.
PHEV – Plug-in Hybrid Electric Vehicles: These hybrids have larger batteries that can be charged by plugging into an external power source. They can run on electric power for a limited distance before switching to the internal combustion engine.
BEV – Battery Electric Vehicles: These vehicles are fully electric and rely only on battery power to operate, with no internal combustion engine.

The projected fleet shares for each decarbonisation scenario, which were explained in Section 3.6, were based on the information provided in the morphological matrices. They represent a progression from low to high decarbonisation efforts, with increasing levels of electrification and consideration for Brazil's unique position regarding ethanol use.

These projections took into account various factors such as:

- In 2024, the ICE (Internal Combustion Engine) vehicles share in the total light vehicle fleet is 99.52%;
- The projected total fleet size of 89,573,554 vehicles in 2050;

- The gradual decrease in ICE vehicle shares from scenario A to E;
- The increasing share of electrified vehicles (HEV, HEV Flex, PHEV, and BEV) across scenarios;
- The emphasis on ethanol use, particularly in scenario D;
- The limit of 50% for ICE vehicles in the High Decarbonisation scenarios (Scenarios C, D and E).

The shares of the EV categories were based on the premisses for the scenarios and on literature from EPE (2023), FENABRAVE (2023), Glyniadakis and Balestieri (2023), IEA (2023c), MME (2023), Safari (2018), Chrispim et al. (2019), Sajid et al. (2021), Santos et al. (2021), Dua et al. (2020), Gan et al. (2021), Thimet et al. (2022), Abdul-Manan et al. (2022), Welch et al. (2019), Sheldon et al. (2022). To assess the impact of using HEVs versus HEVs Flex on the fleet, Scenarios C and D were set to have the same share of PHEVs and BEVs, with scenario C having two times more HEVs than HEVs Flex, and the opposite happening on Scenario D. Table 4.5 presents the shares of the fleet in 2050 for each scenario.

Table 4.5 – LDV fleet 2050 share in each scenario

| | ICE | HEV | HEV Flex | PHEV | BEV |
|---|---|---|---|---|---|
| Scenario A | 67% | 10% | 10% | 8% | 5% |
| Scenario B | 61% | 10% | 12% | 10% | 7% |
| Scenario C | 50% | 16% | 8% | 10% | 16% |
| Scenario D | 50% | 8% | 16% | 10% | 16% |
| Scenario E | 50% | 2% | 6% | 12% | 30% |

As described in Section 3.6, from the current shares of the fleet and the 2050 shares, the growth of the fleet could be projected. Figure 4.10 illustrates the shares of the fleets in each scenario in 2030, 2040 and 2050.

To estimate the potential reduction of GHG emissions for each decarbonisation scenario, the following factors were considered:

- The shift in vehicle fleet composition from ICE to more efficient and electrified options;
- The carbon intensity of Brazil's electricity grid;
- The lifecycle emissions of different vehicle types, considering their energy sources;
- The role of ethanol in Brazil's transport sector.

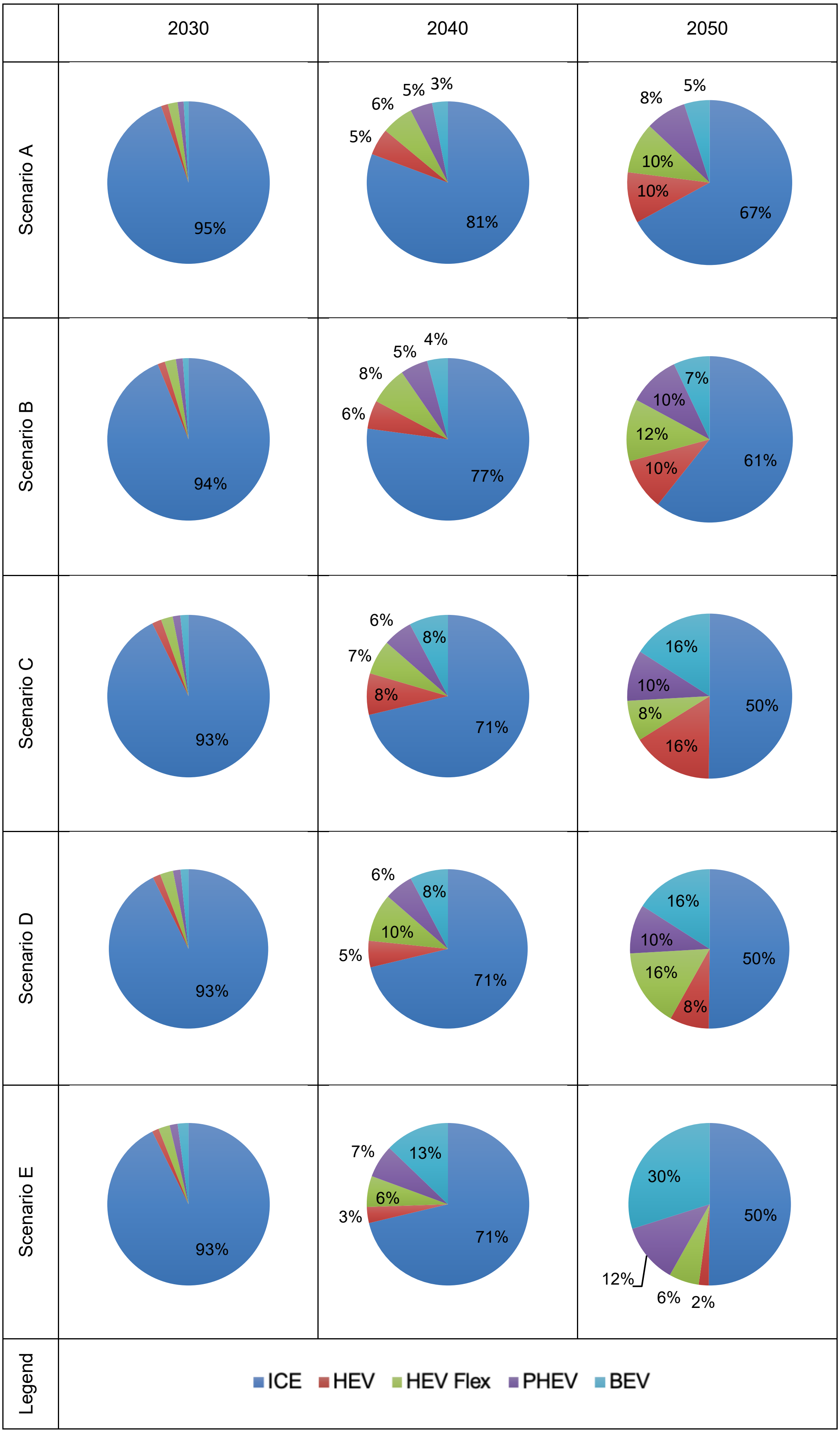


Figure 4.10 - Evolution of the fleet shares for each scenario

The average vehicle consumption rates for each category of vehicle were calculated based on PBE Veicular from INMETRO (2024). The five best selling vehicles in each vehicle category in the first half of 2024 were used to calculate the average consumption.

It is worth noting that the five best selling ICE vehicles in Brazil are all flex fuel, and all either compact or medium sized vehicles in INMETRO's classification. Current sales for HEV, HEV Flex and PHEV categories have a large quantity of extra-large (*Extra grande*) vehicles, large sport utility vehicles (*Utilitário esportivo grande*) and some large sport utility 4x4s, which naturally have higher consumption rates than compacts and mediums, due to weight and size. For this reason, in the case of HEVs and HEVs Flex, only the five best selling vehicles up to the "Large" size category were used. In the PHEV case, large sport utility and extra-large vehicles had to be used, since there were no compact, medium or large sales of these vehicles in the first half of 2024.

INMETRO's consumption tests are performed in new vehicles. ICE vehicles lose efficiency over time, accounting for up to 9% after 300,000 km (Koszalka and Krzaczek, 2022). With the average age of vehicles in Brazil reaching more than 11 years (AutoIndustria, 2024), it was assumed that the average vehicle will consume 9% more than INMETRO's rates. Tables 4.6-4.10 show the average vehicle consumption data in mega joules per kilometre (MJ/km).

Table 4.6 – ICE vehicle consumption

| ICE | | | |
|---|---|---|---|
| Model | Classification | Fuel | Consumption (MJ/km) |
| Fiat Strada | Compact pick-up | Flex | 1.77 |
| VW Polo | Medium | Flex | 1.62 |
| Chevy Onix | Medium | Flex | 1.71 |
| Hyundai HB20 | Compact | Flex | 1.72 |
| Fiat Argo | Compact | Flex | 1.69 |
| | | | **1.70** |

Sources: Autoesporte (2024); ABVE (2024d); INMETRO (2024)

Table 4.7 – HEV consumption

| HEV | | | |
|---|---|---|---|
| Model | Class. | Fuel | Consumption (MJ/km) |
| Honda Civic Hyb TRNG | Large | Gasoline | 1.32 |
| Kia Niro HEV 1.6 SX | Large | Gasoline | 1.20 |
| Hyundai Kona LTD HEV | Medium | Gasoline | 1.21 |
| Kia Niro HEV 1.6 EX | Large | Gasoline | 1.20 |
| Lexus UX250H Luxury | Large | Gasoline | 1.45 |
| | | | **1.28** |

Sources: ABVE (2024d); INMETRO (2024)

Table 4.8 – HEV Flex consumption

| HEV Flex | | | |
|---|---|---|---|
| Model | Class. | Fuel | Consumption (MJ/km) |
| Toyota Ccross XRX Hybrid | Large | Flex | 1.42 |
| Toyota Corolla APremiumH | Large | Flex | 1.32 |
| Toyota Ccross XRV Hybrid | Large | Flex | 1.42 |
| Toyota Corolla Altis HV | Large | Flex | 1.32 |
| | | | **1.37** |

Sources: ABVE (2024d); INMETRO (2024*)*

Table 4.9 – PHEV consumption

| PHEV | | | |
|---|---|---|---|
| Model | Classification | Fuel | Consumption (MJ/km) |
| BYD Song Plus GS DM | Large sport utility | Gasoline | 0.71 |
| GWM Haval H6 Prem PHEV | Large sport utility | Gasoline | 0.82 |
| GWM Haval H6 GT | Extra Large | Gasoline | 0.84 |
| CAOACherry Tiggo8 PHEV | Large sport utility | Gasoline | 0.73 |
| BMW X3 XDrive 30E | Large sport utility 4x4 | Gasoline | 1.11 |
| | | | **0.84** |

Sources: ABVE (2024d); INMETRO (2024)

Table 4.10 – BEV consumption

| BEV | | |
|---|---|---|
| Modelo | Classification | Battery consumption (MJ/km) |
| BYD Dolphin Mini GS EV | Sub-compact | 0.41 |
| BYD Dolphin GS 180EV | Medium | 0.42 |
| GWM Ora 03 Skin BEV48 | Medium | 0.52 |
| GWM Ora 03 GT BEV63 | Medium | 0.51 |
| BYD Dolphin Plus 310EV | Medium | 0.51 |
| Average (MJ/km): | | **0.47** |

Sources: ABVE (2024d); INMETRO (2024)

The rate of gasoline versus ethanol being used in flex fuel vehicles was calculated based on the total amount of automotive gasoline and ethanol consumption from EPE (2024), shown on Table 4.11. Based on this consumption, the proportion of gasoline versus ethanol usage in the average ICE vehicle was assumed to be of 62% gasoline and 38% ethanol.

Table 4.11 – Total LDV fleet fuel consumption in 2022

| Fuel | Annual consumption | % |
|---|---|---|
| Automotive gasoline | 25,873x10$^3$ toe/year | 62% |
| Anhydrous ethanol | 6,865x10$^3$ toe/year | 16% |
| Hydrated ethanol | 9.241x10$^3$ toe/year | 22% |

Source: EPE (2024)

In the case of HEVs, consumption was calculated based on the mandated ratio of ethanol on gasoline sold to the final consumer in Brazil, of 27.5%. For PHEV consumption, according to the ICCT (2022), PHEV users spend on average only 45% to 49% of the time using battery power. Considering this, a 50% rate of battery usage $U_b$ in PHEVs was assumed. As for the efficiency in converting energy, the study by Albatayneh et al. (2020), suggests EVs convert 77% to 91% of electrical energy from the grid to power at the wheels, compared to 12% to 30% from fuel to wheels on ICEs. Assuming an 80% efficiency for EVs and 30% for ICEs, it was assumed that 62% of the energy consumed by a PHEV comes from the ICE, and 38% from the battery. Table 4.12 shows the consumption from each source for the vehicles.

Table 4.1 – Flex fuel vehicle gasoline versus ethanol average estimated consumption

| | Gasoline consumption (MJ/km) | Ethanol consumption (MJ/km) | Electricity consumption (MJ/km) |
|---|---|---|---|
| ICE | 1.05 | 0.65 | - |
| HEV | 0.92 | 0.35 | - |
| HEV Flex | 0.84 | 0.52 | - |
| PHEV | 0.38 | 0.14 | 0.32 |
| BEV | - | - | 0.47 |

From the vehicle consumption from each fuel in each vehicle category, and the shares of the vehicle categories in the total LDV fleet through the years up to 2050, it was possible to project the total LDV fleet consumption from 2025 to 2050. Figures 4.11-4.13 illustrate the energy consumption in tonnes of oil equivalent (toe) in each scenario from gasoline, ethanol and electricity, respectively, and Figure 14 illustrates the total energy consumption in each scenario.

In Figure 4.11 it is possible to visualise how gasoline consumption decreases progressively from the least ambitious scenarios to the most ambitious.

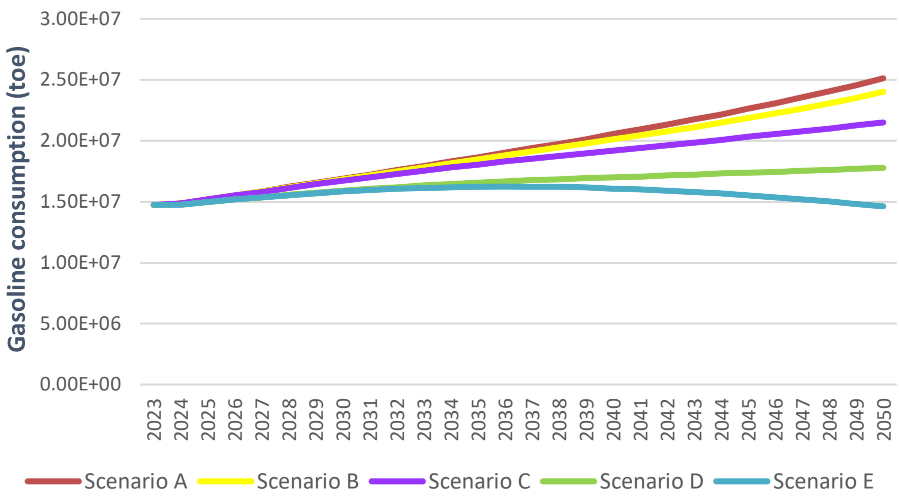


Figure 4.11 – Total gasoline consumption in each scenario

Figure 4.12 reflects the highly effective ethanol policies in Scenario D, as well as the increasing influence of BEVs in Scenario E.

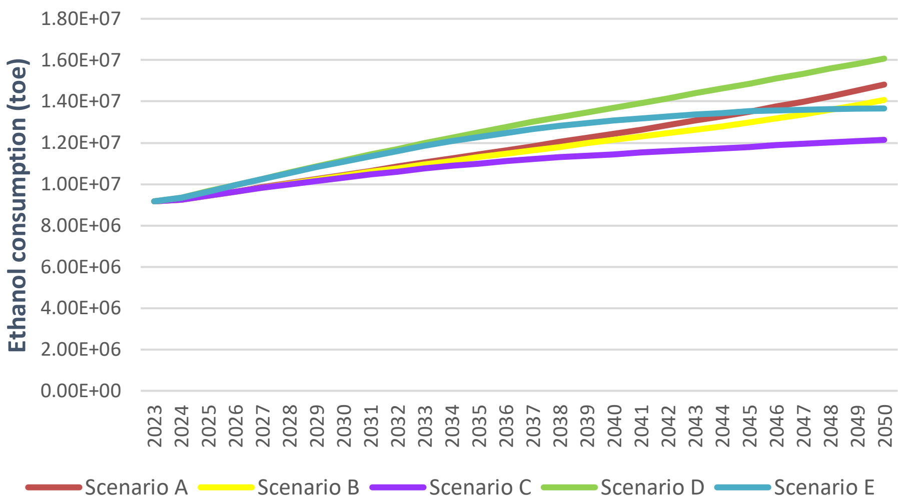


Figure 4.12 – Total ethanol consumption in each scenario

Figure 4.13 illustrates the increase in electricity consumption in the fleet as the share of EVs increases from the least ambitious to the most ambitious scenarios.

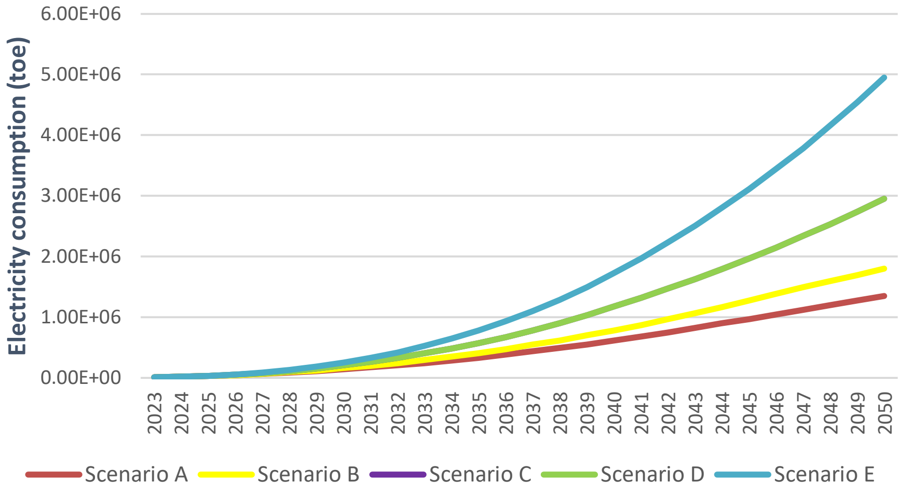


Figure 4.13 – Total electricity consumption in each scenario

Finally, Figure 4.14 shows how the total energy consumption from the LDV fleet decreases from the least ambitious to the most ambitious scenarios, a reflection of the better efficiency of EVs in converting energy.

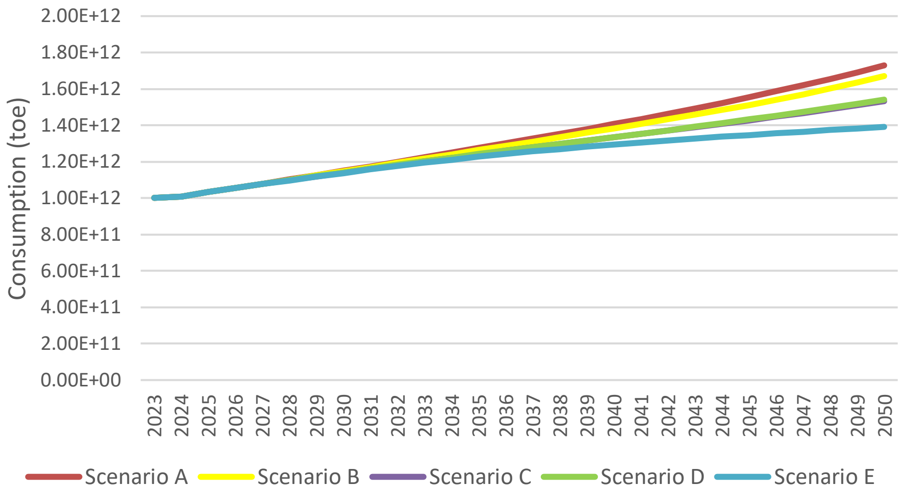


Figure 4.14 – Total energy consumption from the LDV fleet in each scenario

Figures 4.15-4.19 also illustrate the total consumption in each scenario and the share of each fuel.

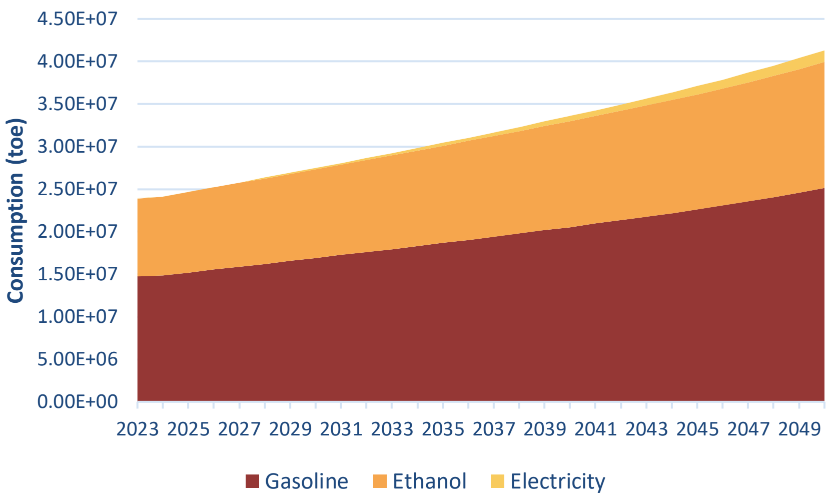


Figure 4.15 – Scenario A consumption

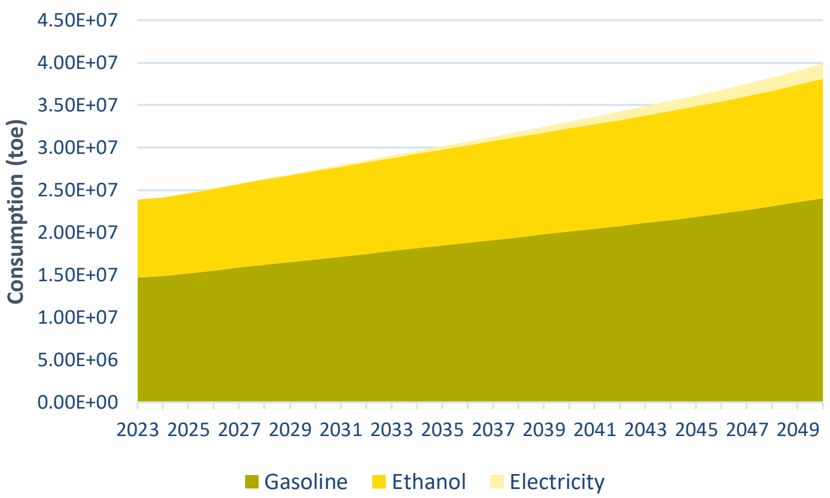


Figure 4.16 – Scenario B consumption

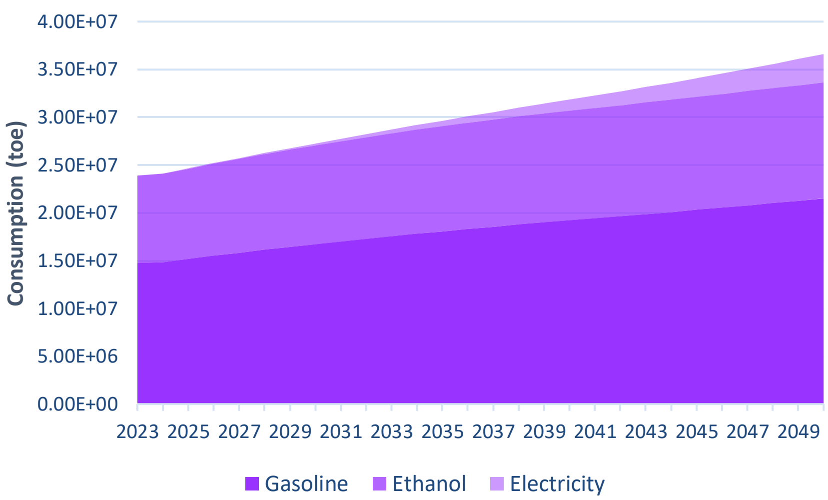


Figure 4.17 – Scenario C consumption

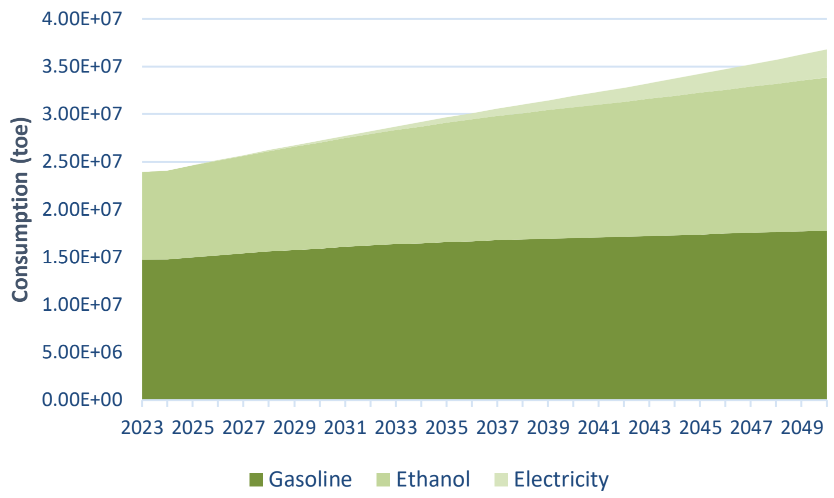


Figure 4.18 – Scenario D consumption

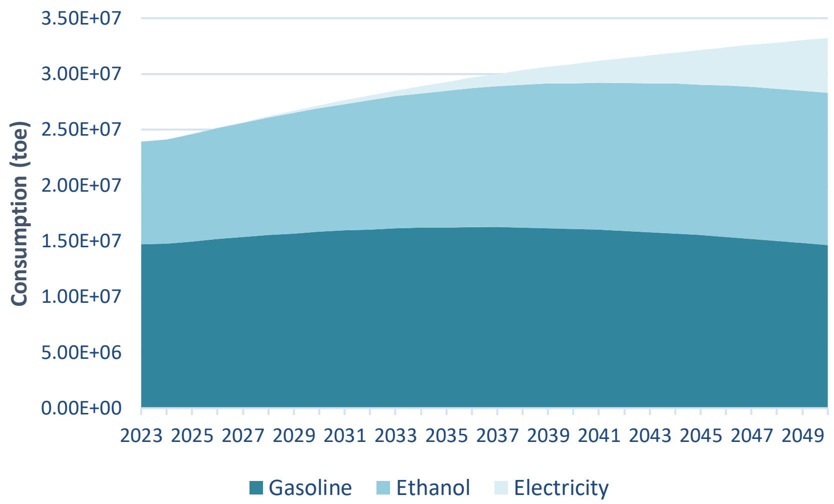


Figure 4.19 – Scenario E consumption

The consumption was then multiplied by the average total annual km driven annually, which in Brazil is 12,900 km, according to Fenabrave (2020). The emission factors were taken from the report by Facto Energy/PUC-Rio (2023), based on scenario 31 from PNE 2050 by EPE (2020). Figures 4.20-4.24 illustrate the total GHG emissions in tonnes of $CO_2$ equivalent ($tCO_2e$) in each scenario and the share of each fuel. From these figures, it is possible to visualise the outsized influence of gasoline in GHG emissions. Figure 4.25 shows the total emissions in each scenario.

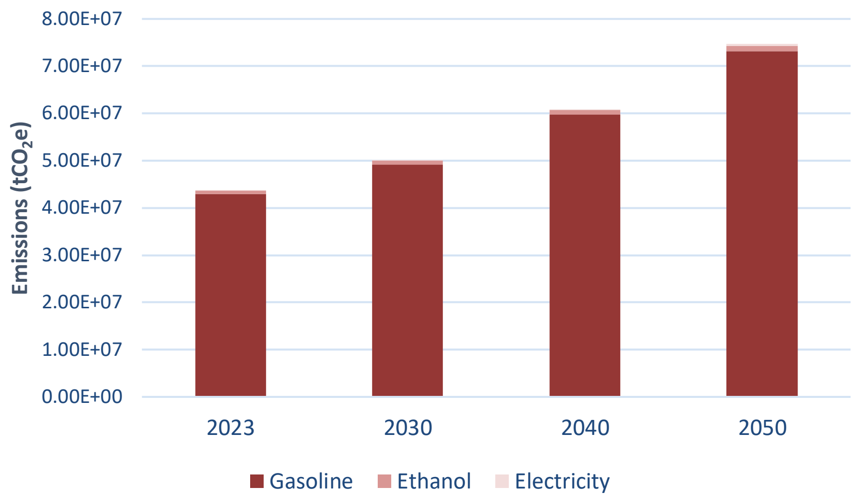


Figure 4.20 – Scenario A fleet emissions

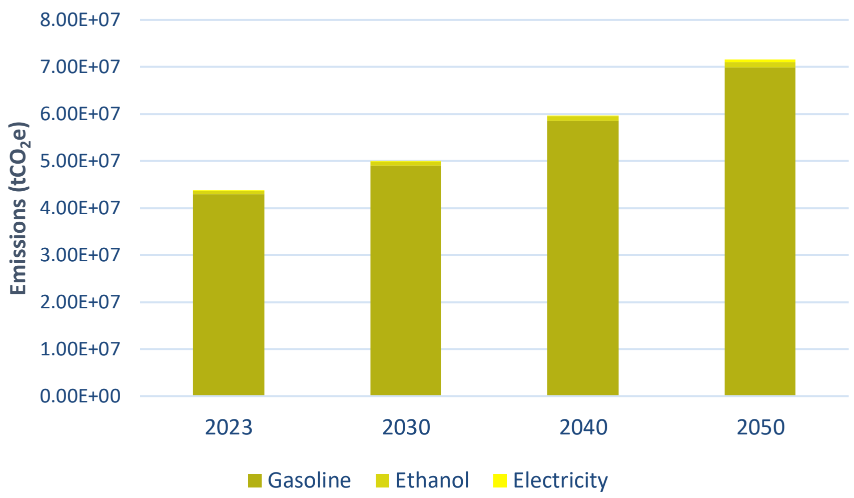


Figure 4.21 – Scenario B fleet emissions

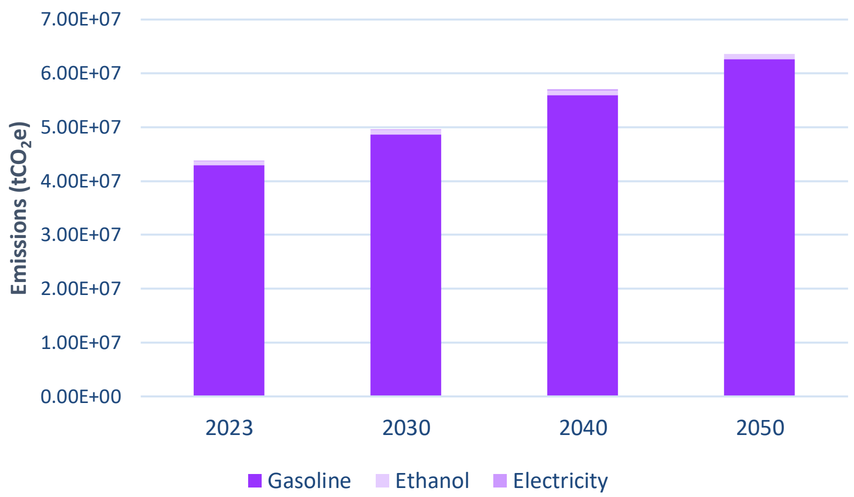


Figure 4.22 – Scenario C fleet emissions

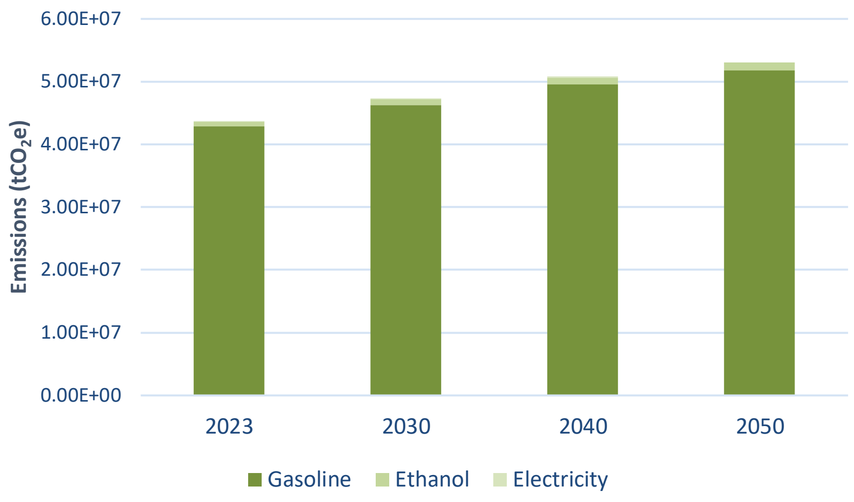


Figure 4.23 – Scenario D fleet emissions

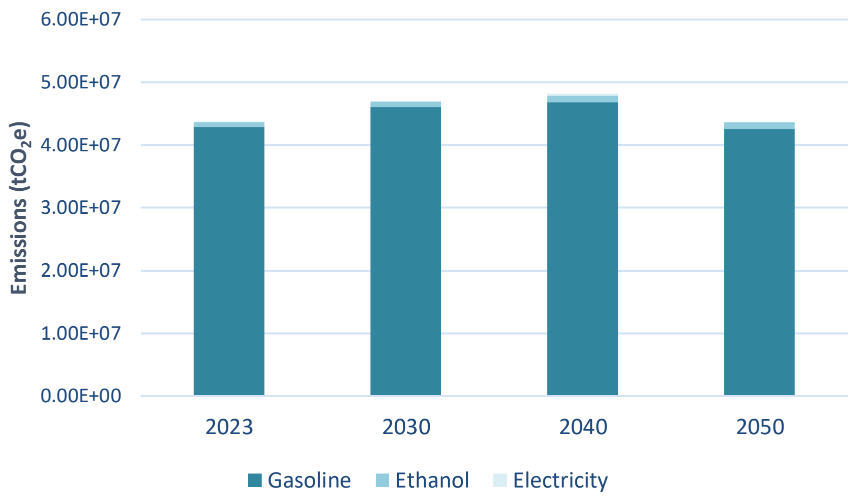


Figure 4.24 – Scenario E fleet emissions

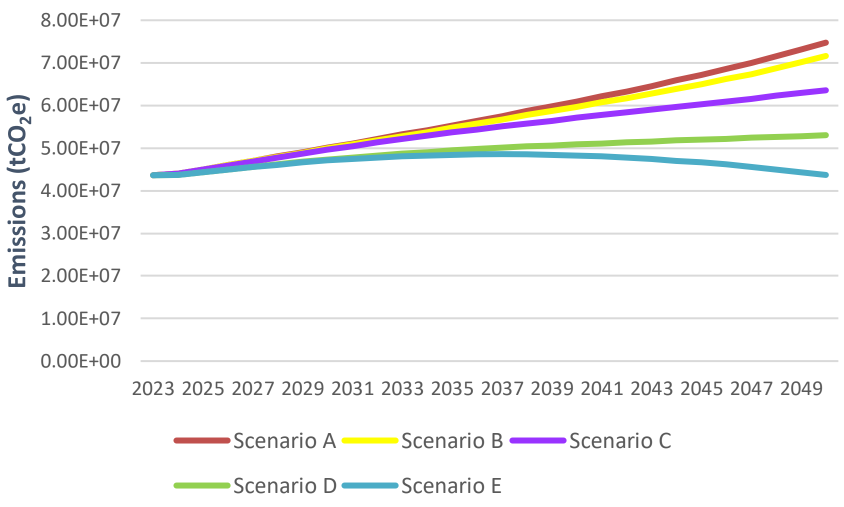


Figure 4.25 – Total emissions in each scenario

In scenario A “Low decarbonisation with low electrification”, 33% of the fleet is electrified (including hybrids) in 2050. The estimated GHG emission reduction is 7.0%, because the small shift to electrified vehicles will provide some emissions reduction, but it's limited. Improvements in ICE efficiency might contribute to this reduction as well. Glyniadakis and Balestieri (2023) suggest that even in low electrification scenarios, some GHG reduction is achievable due to efficiency improvements, while IEA (2023) indicates that even small increases in EV adoption can lead to emissions reductions.

Scenario B “Moderate decarbonisation with low electrification” sees 39% of the fleet electrified in 2050, with a significant increase in hybrids and plug-in hybrids. The estimated GHG emission reduction is 8.8% due to the increased adoption of hybrids and plug-in hybrids that will provide more significant emissions reductions. The continued use of ethanol in flex-fuel vehicles also contributes to lower emissions. Chrispim et al. (2019) discuss the emissions reduction potential of electric and hybrid vehicles in Brazil and Santos et al. (2021) highlight the role of ethanol in reducing GHG emissions in Brazil's transportation sector.

In scenario C “High decarbonisation with moderate electrification”, 50% of the fleet is electrified in 2050, with a more balanced distribution among HEVs, PHEVs, and BEVs. In this scenario, the higher proportion of fully electric vehicles, combined with improvements in grid carbon intensity, will lead to more substantial emissions reductions reaching 12.8%. Gan et al. (2021) discuss the emissions reduction potential of increasing EV adoption, considering grid carbon intensity, while Lap et al. (2020) explore scenarios for Brazil's future electricity mix, which would impact EV emissions.

Scenario D “High decarbonisation with moderate electrification plus ethanol” has 50% electrification, with a strong emphasis on flex-fuel hybrids (16% of the fleet), as well as increased use of ethanol in the LDV fleet. The current share of ethanol in consumption from the LDV increases from 38% to 50% in 2050. The combination of increased electrification and a strong focus on ethanol use in flex-fuel hybrids can lead to significant emissions reductions (21.3%). Sajid et al. (2021) discuss the role of biofuels in sustainable development and emissions reduction in Brazil and Benvenutti et al. (2017) explore the diffusion of alternative fuel vehicles in Brazil and their potential impact on emissions.

Finally, in the most ambitious scenario “High decarbonisation with high electrification”, 50% of the fleet will be electrified, including a high proportion of PHEVs and BEVs. Estimated GHG emission reduction will reach 25.7% due to the high proportion of fully electric and plug-in hybrid vehicles, combined with expected improvements in grid carbon intensity and continued use of ethanol, could lead to substantial emissions reductions. Abdul-Manan et al. (2022) discuss the relationship between grid decarbonisation and EV emissions reductions and Sheldon et al. (2022) analyse the effectiveness of EV subsidies in reducing $CO_2$ emissions, which is relevant to high electrification scenarios.

Table 4.13 shows the GHG emissions reduction in years 2030, 2040 and 2050, while Table 4.14 shows the accumulated reductions in the same years, from a BAU scenario.

Table 4.13 – GHG emissions reduction in years 2030, 2040 and 2050

| Scenario | 2030 reduction | 2040 reduction | 2050 reduction |
|---|---|---|---|
| A | 2.0% | 7.5% | 12.7% |
| B | 2.3% | 9.3% | 16.3% |
| C | 2.9% | 13.3% | 25.7% |
| D | 7.5% | 22.8% | 38.0% |
| E | 7.9% | 26.8% | 49.0% |

Table 4.14 - Accumulated GHG emissions reduction in years 2030, 2040 and 2050

| Scenario | 2030 accumulated reduction | 2040 accumulated reduction | 2050 accumulated reduction |
|---|---|---|---|
| A | 1.1% | 3.7% | 7.0% |
| B | 1.3% | 4.5% | 8.8% |
| C | 1.5% | 6.1% | 12.8% |
| D | 4.5% | 12.2% | 21.3% |
| E | 4.7% | 13.7% | 25.7% |

## 4.7. Description of decarbonisation scenarios for the Brazilian light-duty vehicle fleet: three trajectories

Drawing on the morphological matrices presented in Figures 4.4–4.8 and the roles of key actors outlined in Table 4.2, this section articulates five distinct decarbonisation scenarios for the Brazilian light vehicle fleet, projected to 2050.

These scenarios are systematically structured along three temporally demarcated trajectories: (i) a near-term trajectory (2025–2030), which elucidates the initial transformative processes and developmental patterns within each scenario; (ii) a medium-term trajectory (2031–2040), which expounds upon the evolution of these early changes; and (iii) a long-term trajectory (2041-2050), which delineates the culmination of these transformations, ultimately converging on the projected outcomes for 2050. This tripartite temporal framework enables a nuanced analysis of the dynamic interplay between policy interventions, technological advancements, and socioeconomic factors across different time horizons.

The narrative format for describing the decarbonisation scenarios facilitates a clearer understanding of how decisions and actions taken during the 2025–2030 period will shape medium- and long-term outcomes by 2040 and 2050, respectively. It also offers a more realistic timeline for the formulation and implementation of policies as well as technological and infrastructural advancements. Each scenario presents a coherent progression from the current state (2024) to the medium- and long-term outcomes, with the key variables and stakeholder actions highlighted throughout the analysis.

### 4.7.1. Scenario A – Low decarbonisation with low electrification

This scenario envisions a future where Brazil's transition to EVs proceeds at a sluggish pace, with minimal changes from the current situation. It reflects a conservative approach, prioritizing established technologies and infrastructures over rapid innovation.

The scenario is characterized by limited policy support for electrification, continued dominance of ICE vehicles, and slow development of charging infrastructure. Public attitudes remain sceptical towards EVs, while the automotive industry maintains its focus on traditional technologies. This scenario represents a cautious trajectory, where economic considerations and established practices take precedence over aggressive decarbonisation efforts.

#### Trajectory 2025-2030

In this initial phase, Brazil's LDV sector sees minimal change. The government maintains a hands-off approach, offering no new incentives for EV adoption (Light-duty EV policy support - EVPO) or plans for ICE sales phaseout (ICES).

Automotive manufacturers continue to focus on ICE vehicles, with only token investments in EV technology. The National Electric Energy Agency (ANEEL) makes no significant changes to electricity pricing structures (ELEP), providing no incentives for off-peak EV charging.

Energy companies make only minor adjustments to the grid (TRDI), focusing on maintaining existing infrastructure. Charging infrastructure (INFR) remains limited with few stations mostly in urban areas. EV ownership costs (COST) remain high due to lack of scale and incentives. Consumers show little interest in EVs (PREF), with adoption rates barely increasing.

The ethanol industry maintains its production levels without significant innovation. Research into EV technologies and battery recycling (RECY) progresses slowly due to limited funding. By 2030, ICE vehicles still dominate over 90% of the fleet, with electrified vehicles (including hybrids) making up less than 10%.

The pace of change remains slow from 2031 to 2040. Government policies continue to favour ICE vehicles, with only minor adjustments to regulations. Automotive manufacturers maintain their focus on ICE technology, with minimal investment in EVs.

Grid infrastructure sees gradual, reactive upgrades to handle increasing power demands, but not specifically for EV charging. Charging infrastructure expands slowly, primarily in wealthy urban areas. EV costs decrease marginally due to global trends, but remain significantly higher than ICE vehicles in Brazil. Consumer preference for ICE vehicles persists, with EVs seen as a niche product.

The ethanol industry continues to play a significant role in the fuel mix, but with limited improvements in efficiency or environmental impact. Research institutions make incremental progress in EV and battery technologies, but Brazil remains a follower rather than a leader in these areas.

**Trajectory 2031-2040**

The pace of change remains slow from 2031 to 2040. Government policies continue to favour ICE vehicles, with only minor adjustments to regulations. Automotive manufacturers maintain their focus on ICE technology, with minimal investment in EVs.

Grid infrastructure sees gradual, reactive upgrades to handle increasing power demands, but not specifically for EV charging. Charging infrastructure expands slowly, primarily in wealthy urban areas. EV costs decrease marginally due to

global trends, but remain significantly higher than ICE vehicles in Brazil. Consumer preference for ICE vehicles persists, with EVs seen as a niche product.

The ethanol industry continues to play a significant role in the fuel mix, but with limited improvements in efficiency or environmental impact. Research institutions make incremental progress in EV and battery technologies, but Brazil remains a follower rather than a leader in these areas. By 2040, ICE vehicles still represent over 80% of the fleet, with electrified vehicles comprising less than 20%.

#### Trajectory 2041-2050

In the final decade, the transition to EVs gains slightly more momentum, but still lags significantly behind global trends. The government introduces modest incentives for EV adoption, primarily in response to international pressure. Automotive manufacturers begin to offer more hybrid models, but full EVs remain a small portion of their product lines.

Grid infrastructure improvements accelerate somewhat, with some smart grid technologies implemented in major urban areas. Charging infrastructure expands more rapidly, but remains concentrated in cities and along major highways. EV costs continue to decrease, narrowing the gap with ICE vehicles, but not achieving parity.

Public perception of EVs improves gradually, driven by global trends and increasing visibility. The ethanol industry begins to explore synergies with electrification, such as flex-fuel hybrids. Research institutions increase their focus on EV technologies, but Brazil still lags behind global leaders.

By 2050, ICE vehicles represent 67% of the fleet, with electrified vehicles comprising 33%. The potential yearly GHG emissions reduction reaches 12.7%, and accumulated emissions reduction reaches just 7% compared to a business-as-usual (BAU) scenario.

### 4.7.2.
### Scenario B – Moderate decarbonisation with low electrification

This scenario portrays a future where Brazil takes cautious steps towards vehicle electrification and decarbonisation. It reflects a balanced approach, attempting to modernize the automotive sector while maintaining support for established industries like ethanol production. The scenario is characterized by moderate policy support for EVs, a gradual shift in market dynamics, and incremental improvements in infrastructure. Public attitudes evolve slowly towards acceptance of EVs, while the automotive industry begins to diversify its offerings. This scenario represents a middle-ground trajectory, where decarbonisation efforts progress steadily but without dramatic shifts, balancing economic considerations with environmental goals.

#### Trajectory 2025-2030

This period sees the beginnings of change in Brazil's automotive sector. The government introduces modest incentives for EV adoption (EVPO) and begins discussions on long-term ICE phase-out plans (ICES).

These policy shifts encourage automotive manufacturers to increase investment in EV and hybrid technology, although their primary focus remains on ICE vehicles. ANEEL starts to consider EV charging in electricity pricing structures (ELEP), implementing small adjustments to encourage off-peak charging. Energy companies begin planning grid upgrades to handle increased EV charging demand (TRDI), focusing on urban areas.

Charging infrastructure providers start expanding their networks (INFR), primarily in cities and along major highways. EV ownership costs (COST) begin to decrease slightly due to modest government incentives and increasing production scales.

Consumers' attitudes towards EVs (PREF) start to shift from resistance to curiosity, with early adopters embracing the technology. The ethanol industry maintains strong production while beginning to research more efficient production methods.

Research institutions increase their focus on EV technologies, leading to gradual improvements in battery technology (RECY) and vehicle autonomy (Vehicle autonomy for EVs - AUTO).

#### Trajectory 2031-2040

From 2031 to 2040, the pace of change accelerates moderately. Government policies supporting EV adoption become more robust, although still not aggressive. The 2030 energy efficiency targets set by the National Energy Efficiency Plan (PNEf) drive some policy changes. Automotive manufacturers increase their investment in EV and hybrid technologies, leading to a wider range of models available to consumers.

Grid infrastructure sees more significant upgrades, with energy companies proactively preparing for increased EV charging demands. Charging infrastructure continues to expand, becoming more common in urban and suburban areas, and along major transportation corridors. EV costs decrease more substantially, narrowing the gap with ICE vehicles. Consumer preference gradually shifts towards EVs, driven by improved performance, lower costs, and growing environmental awareness.

The ethanol industry continues to play a significant role, with advancements in production efficiency and sustainability. Research institutions make steady progress in EV and battery technologies, bringing Brazil closer to global standards in these areas.

### Trajectory 2041-2050

In the final decade, the transition to EVs gains more significant momentum. The government implements stronger incentives for EV adoption and sets clear timelines for phasing out new ICE vehicle sales, aligning with the 2045 ICE sales phaseout milestone. Automotive manufacturers shift a larger portion of their production to EVs and advanced hybrids.

Grid infrastructure undergoes substantial modernization, with widespread implementation of smart grid technologies to manage EV charging efficiently. Charging infrastructure becomes ubiquitous in urban areas and along all major highways, alleviating range anxiety concerns. EV costs reach parity with ICE vehicles, driven by technological advancements and economies of scale.

Public perception strongly favours EVs, with environmental concerns and improved performance driving adoption. The ethanol industry successfully transitions to producing advanced biofuels, complementing the electrification of light vehicles. Research institutions establish Brazil as a significant player in EV and battery technologies, with growing domestic production capabilities.

By 2050, ICE vehicles' fleet share has decreased to 61%, with electrified vehicles comprising 39% of the fleet. The yearly GHG emissions reduction potential reaches 16.3%, and the accumulated reduction reaches 8.8% compared to a BAU scenario, driven by the higher adoption of hybrid and plug-in hybrid vehicles.

### 4.7.3. Scenario C – High decarbonisation with moderate electrification

This scenario envisions a future where Brazil makes significant strides in decarbonising its LDV fleet through a combination of electrification and other efficiency measures. It reflects an ambitious approach, prioritizing environmental goals while leveraging the country's unique strengths in renewable energy and biofuels.

The scenario is characterized by strong policy support for EVs, rapid technological advancements, and substantial infrastructure development. Public attitudes shift decisively in favour of sustainable transport options, while the automotive industry undergoes a major transformation. This scenario represents a progressive trajectory, where decarbonisation efforts are prioritized, driving innovation and economic opportunities in the clean transport sector.

#### Trajectory 2025-2030

This period marks the beginning of a significant shift in Brazil's automotive landscape. The government implements strong incentives for EV adoption (EVPO) and announces clear timelines for an ICE phaseout (ICES). These decisive actions prompt automotive manufacturers to accelerate their shift towards EV and hybrid vehicle production. ANEEL develops new pricing structures to encourage off-peak EV charging (ELEP).

Energy companies respond by initiating substantial investments in grid infrastructure to support growing EV charging demands (TRDI). Charging infrastructure providers rapidly expand their networks (INFR), focusing on urban and suburban areas, and beginning to cover major highways. EV ownership costs (COST) start to decrease significantly due to government incentives, increasing production scales, and technological advancements.

Consumer attitudes towards EVs (PREF) shift positively, driven by improved performance, lower costs, and growing environmental awareness. The ethanol industry begins to diversify, investing in research for advanced applications of ethanol in transportation. Research institutions conduct extensive research on EV technologies, leading to notable improvements in battery technology (RECY) and vehicle autonomy (AUTO).

### Trajectory 2031-2040

From 2031 to 2040, the transformation of Brazil's LDV sector accelerates dramatically. Government policies strongly support EV adoption, with ambitious targets set for renewable energy integration and emissions reductions. The automotive industry shifts the majority of its resources to EV and hybrid vehicle production, with several manufacturers announcing plans to phase out ICE vehicle production entirely.

Grid infrastructure undergoes a major overhaul, with energy companies implementing smart grid technologies to manage the growing EV charging demand efficiently.

Charging infrastructure becomes widespread, covering urban, suburban, and rural areas, as well as all major highways. EV costs reach parity with ICE vehicles, driven by economies of scale and continued technological improvements.

Consumer preference strongly shifts towards EVs, driven by superior performance, lower total cost of ownership, and environmental concerns. The ethanol industry successfully transitions to producing advanced biofuels for aviation and heavy industry, complementing the electrification of light vehicles.

Research institutions establish Brazil as a significant player in EV and battery technologies, with domestic production capabilities growing substantially.

### Trajectory 2041-2050

In the final decade, Brazil emerges as a leader in sustainable transportation. The government implements policies to phase out ICE vehicle sales entirely by 2050, aligning with global decarbonisation efforts. The automotive industry completes its transition to EV and advanced hybrid production, with Brazil becoming a major exporter of clean vehicle technologies. Grid infrastructure is fully modernized, with advanced smart grid systems optimizing energy distribution and integrating a high percentage of renewable sources.

Charging infrastructure is ubiquitous, including innovative solutions like wireless charging roads and ultra-fast charging stations. EV performance and range surpass traditional ICE vehicles in all aspects, and costs continue to decrease. Public perception overwhelmingly favours EVs, with ICE vehicles becoming increasingly rare on roads. The ethanol industry becomes a world leader in advanced biofuel production, significantly contributing to Brazil's energy matrix and export economy. Research institutions in Brazil lead global innovation in EV technologies, battery recycling, and sustainable transportation systems.

By 2050, ICE vehicles' share of the fleet has decreased to 50%, with electrified vehicles comprising the other 50%. The yearly GHG emissions reduction potential reaches 25.7%, and the accumulated reductions reach 12.8%, driven by the high adoption of EVs, improved grid efficiency, and the integration of renewable energy sources.

### 4.7.4. Scenario D – High decarbonisation with moderate electrification plus ethanol

This scenario presents a future in which Brazil achieves high decarbonisation through a unique combination of electrification and increased use of ethanol in flex-fuel vehicles. It reflects an innovative approach that leverages Brazil's strengths in biofuel production while embracing electric vehicle technology.

The scenario is characterized by strong policy support for both EVs and advanced ethanol technologies, rapid advancements in flex-fuel hybrid vehicles, and comprehensive infrastructure development. Public attitudes strongly favour sustainable transport options, recognizing the complementary roles of electrification and biofuels. The automotive industry undergoes a transformation focused on developing advanced flex-fuel hybrid technologies alongside pure EVs. This scenario represents a distinctly Brazilian path to decarbonisation, balancing technological innovation with the country's established biofuel industry.

#### Trajectory 2025-2030

This period sees Brazil charting a unique path in vehicle decarbonisation. The government implements strong support for both EV adoption and ethanol use (EVPO), with policies particularly encouraging flex-fuel hybrid vehicles. This balanced approach prompts automotive manufacturers to accelerate development of advanced flex-fuel hybrid vehicles alongside pure EVs.

ANEEL develops electricity pricing structures that support both EV charging and ethanol production and energy companies begin investing in grid infrastructure for EV charging (TRDI) while also supporting energy generation from ethanol production waste.

Charging infrastructure providers expand their networks (INFR) while also beginning to develop integrated fuelling stations for both electricity and ethanol. EV and flex-fuel hybrid ownership costs (COST) start to decrease due to government incentives and increasing production scales.

Consumer interest in flex-fuel hybrid vehicles grows rapidly (PREF), appreciating the flexibility and reduced environmental impact. The ethanol industry significantly increases investment in more efficient and sustainable production methods.

Research institutions focus on optimizing flex-fuel hybrid technologies and sustainable ethanol production, leading to improvements in battery technology (RECY) and vehicle performance (AUTO).

### Trajectory 2031-2040

From 2031 to 2040, Brazil's unique approach to decarbonisation gains momentum. Government policies continue to support both electrification and advanced ethanol technologies, with new regulations promoting the integration of these technologies. Policies to phase out traditional ICE vehicle sales by 2040 are implemented, while the support for advanced flex-fuel hybrid technologies continues.

The automotive industry focuses primarily on advanced flex-fuel hybrid vehicles and pure EVs, with ICE vehicle production declining sharply. Grid infrastructure undergoes major upgrades to support widespread EV charging, while also integrating distributed energy generation from ethanol production.

Charging and fuelling infrastructure becomes increasingly integrated, with stations offering both electricity and ethanol becoming common throughout the country.

The costs of EVs and advanced flex-fuel hybrids decrease significantly, reaching parity with traditional ICE vehicles. Consumer preference strongly shifts towards these vehicles, driven by their flexibility, lower operating costs, and minimal environmental impact.

The ethanol industry becomes a world leader in advanced biofuel production, significantly contributing to Brazil's energy matrix.

Research institutions establish Brazil as a global leader in flex-fuel hybrid technologies and sustainable biofuel production, alongside advancements in pure EV technology. In 2040,

### Trajectory 2041-2050

In the final decade, Brazil's innovative approach to decarbonisation proves highly successful. The automotive industry in Brazil becomes a global leader in producing highly efficient flex-fuel hybrid vehicles and pure EVs, exporting these technologies worldwide.

Grid infrastructure is fully modernized, with smart systems optimizing the integration of electricity from both centralized renewable and distributed ethanol-based generation. Charging and fuelling infrastructure is ubiquitous and fully integrated, offering consumers seamless choices between electricity and advanced biofuels. The performance and efficiency of flex-fuel hybrid vehicles rival or exceed those of pure EVs in many applications.

Public perception strongly favours these Brazilian-developed sustainable transport solutions. The ethanol industry evolves into a sophisticated biochemical sector, producing not only advanced biofuels but also renewable materials for various industries. Research institutions in Brazil lead global innovation in sustainable transportation systems, combining electric, flex-fuel, and other emerging technologies.

By 2050, ICE vehicles' share of the fleet has decreased to 50%. Electrified vehicles, including a significant portion (16%) of advanced flex-fuel hybrids, BEVs and PHEVs, make up the other 50%. The yearly GHG emissions reduction potential reaches 38.0 %, with the accumulated reductions reaching 21.3%, driven by the combined benefits of electrification and advanced biofuel use.

### 4.7.5.
### Scenario E – High decarbonisation with high electrification

This scenario represents the most ambitious and transformative path for Brazil's light vehicle fleet, positioning the country at the forefront of global efforts to combat climate change through sustainable transportation. It envisions a future in which Brazil fully embraces electric vehicle technology, achieving the highest level of decarbonisation among all scenarios.

The scenario is characterized by aggressive policy support for EVs, breakthrough technological advancements, and massive infrastructure overhaul. Public attitudes shift dramatically in favour of EVs, while the automotive industry undergoes a complete transformation. This scenario represents the most progressive trajectory, where decarbonisation efforts through electrification are maximized, driving unprecedented innovation and reshaping Brazil's entire transportation landscape.

**Trajectory 2025-2030**

This period marks the beginning of a dramatic shift in Brazil's automotive landscape. The government implements aggressive incentives for EV adoption (Light-duty EV policy support - EVPO) and announces an ambitious timeline for ICE phase-out (ICE sales phaseout - ICES), targeting 2040. These bold actions prompt automotive manufacturers to rapidly pivot towards EV production. ANEEL develops innovative pricing structures to encourage EV charging during periods of peak renewable energy generation (Electricity price - ELEP).

Energy companies initiate massive investments in grid infrastructure to support the anticipated surge in EV charging demands (T&D network effectiveness to handle EV charging demands - TRDI). Charging infrastructure providers rapidly expand their networks (Charging infrastructure deployment - INFR), with a focus on creating a comprehensive national charging network. EV ownership costs (EVs ownership costs - COST) start to decrease rapidly due to generous government incentives, economies of scale, and technological breakthroughs.

Consumer attitudes towards EVs (Public preference towards light EVs - PREF) shift dramatically, driven by a combination of environmental concerns, improved performance, and decreasing costs. The ethanol industry begins to explore new applications, including the production of sustainable aviation fuels. Research institutions conduct cutting-edge research on EV technologies, leading to significant advancements in battery technology (Incentives for battery recycling/reuse - RECY) and vehicle autonomy (Vehicle autonomy for EVs - AUTO).

**Trajectory 2031-2040**

From 2031 to 2040, the transformation of Brazil's LDV sector accelerates dramatically. Government policies strongly favour EV adoption, with ambitious targets set for 100% new EV sales by 2040. The automotive industry completely shifts its focus to EV production, with major manufacturers announcing the end of fully ICE vehicle production before 2040.

Grid infrastructure undergoes a complete overhaul, with energy companies implementing advanced smart grid technologies and large-scale energy storage solutions to manage the growing EV charging demand. Charging infrastructure becomes ubiquitous, with fast-charging stations available even in remote areas. EV costs fall below those of ICE vehicles, driven by continued technological improvements and massive economies of scale.

Consumer preference overwhelmingly shifts towards EVs, driven by superior performance, lower total cost of ownership, and strong environmental concerns. The ethanol industry successfully transitions to producing advanced biofuels for aviation and heavy industry, complementing the electrification of light vehicles. Research institutions establish Brazil as a global leader in EV and battery technologies, with domestic production capabilities expanding rapidly.

**Trajectory 2041-2050**

In this final decade, Brazil emerges as a global leader in sustainable transportation, with the light vehicle fleet undergoing a near-complete transformation. The government's ambitious ICE phase-out plan comes into full effect, with sales of new ICE vehicles completely banned by 2040 (ICE sales phaseout - ICES). This policy, combined with aggressive incentives for EV adoption (Light-duty EV policy support - EVPO), accelerates the transition to electric mobility.

The automotive industry in Brazil completes its transition to EV production, with the country becoming a major exporter of advanced EVs and related technologies. Domestic manufacturers introduce groundbreaking EV models tailored to Brazilian conditions, featuring ultra-long range and rapid charging capabilities (Vehicle autonomy for EVs - AUTO). These advancements significantly boost consumer confidence and preference for EVs (Public preference towards light-duty EVs - PREF).

Grid infrastructure reaches new heights of sophistication, with AI-driven smart grid systems optimizing energy distribution and seamlessly integrating a high percentage of renewable sources. V2G technology becomes widespread, allowing

EVs to serve as distributed energy storage units, enhancing grid stability and reducing electricity costs for EV owners (Electricity price - ELEP).

Charging infrastructure (Charging infrastructure deployment - INFR) becomes ubiquitous and highly advanced. Wireless charging roads are implemented on major highways, while ultra-fast charging stations capable of fully charging vehicles in under 10 minutes are commonplace in urban areas (Fuelling/Charging time - CHAR). This extensive infrastructure effectively eliminates range anxiety, further accelerating EV adoption.

The total cost of EV ownership (EVs ownership costs - COST) falls significantly below that of legacy ICE vehicles, driven by economies of scale, technological advancements, and favourable policies. This economic advantage, combined with superior performance and environmental benefits, makes EVs the clear choice for consumers across all income brackets.

Research institutions and the private sector in Brazil lead global innovation in EV technologies, focusing on next-generation batteries with higher energy density and longer life spans. A robust battery recycling and repurposing industry emerges, significantly reducing the environmental impact of EV production (Incentives for battery recycling/reuse - RECY).

By 2050, ICE vehicles' share of the fleet has decreased to 50 %, with electrified vehicles comprising the other 50 %, including a significant portion (30 %) of pure battery electric vehicles. This transformation, coupled with the continued decarbonization of the electricity grid, results in a substantial reduction in GHG emissions. The yearly GHG emissions reduction potential reaches 49.0 %, and the accumulated reductions reach 25.7 %, the highest among all scenarios, driven by the high adoption of EVs, a highly efficient and renewable electricity grid, and advanced energy management systems.

## 4.8. Barriers to implementing electrification of light vehicle fleet in Brazil and strategic implications

This section analyses a set of barriers to the implementation of electrification of LDV fleet in Brazil, identified from the literature review. This analysis includes a discussion of strategic implications and measures to overcome the challenges.

The 16 barriers were classified into four groups: (i) regulatory (2 RBs); (ii) technical (3 TBs); (iii) economic (3 EBs); social (3 SBs); industrial (3 IBs) and environmental (2 EBs).

### 4.8.1. Regulatory barriers (RBs)

**RB1 – Lack of clear ICE phaseout policy**

- Brief description: Absence of a definitive timeline for phasing out internal combustion engine (ICE) vehicles creates uncertainty in the market.
- Key variable: ICES (ICE sales phaseout)
- Key actors: Government and policymakers.
- Discussion and strategic implications: The absence of a definitive timeline for phasing out ICE vehicles creates significant uncertainty in the Brazilian automotive market. Without clear government directives, manufacturers are hesitant to fully commit to EV production, as they cannot accurately forecast the decline of ICE vehicle demand.

This ambiguity also affects consumer behaviour, as potential buyers may delay their transition to EVs, anticipating that ICE vehicles will remain available indefinitely. The lack of a phaseout policy further complicates long-term planning for infrastructure development, such as the expansion of charging networks and grid upgrades. Consequently, this regulatory gap hampers the overall momentum of EV adoption, as both industry players and consumers lack the certainty needed to make confident decisions about transitioning away from ICE vehicles.

This barrier significantly impacts the ICES (ICE sales phaseout) variable and requires proactive engagement from government and policymakers to establish a clear roadmap for the electrification of Brazil's light vehicle fleet.

**RB2 – Insufficient EV policy support**

- Brief description: Inadequate incentives and regulations to promote EV adoption and manufacturing.
- Key variable: EVPO (Light-duty EV policy support)
- Key actors: Government and policymakers and ANEEL
- Discussion and strategic implications: The inadequate incentives and regulations to promote EV adoption and manufacturing in Brazil present a

significant barrier to electrification. Current policy frameworks often fail to provide compelling financial incentives, such as tax breaks or purchase subsidies, that could offset the higher upfront costs of EVs. Additionally, the lack of stringent emissions standards for ICE vehicles reduces the comparative advantage of EVs in the market. Insufficient support for domestic EV manufacturing also hinders the development of a robust local EV industry, potentially increasing reliance on imports and missing opportunities for job creation.

The absence of comprehensive urban planning policies to support EV infrastructure, such as mandates for charging stations in new buildings or parking facilities, further impedes adoption. This policy vacuum affects the EVPO (Light-duty EV policy support) variable significantly, creating an environment where EVs struggle to compete with established ICE vehicles. Addressing this barrier requires coordinated efforts from government bodies, including ANEEL, to create a supportive regulatory ecosystem that accelerates EV adoption and industry growth.

### 4.8.2. Technical barriers (TBs)

#### TB1 – Limited charging infrastructure

- Brief description: Insufficient development of charging stations, particularly in non-urban areas and along highways.
- Key variable: INFR (Charging infrastructure deployment).
- Key actors: Charging infrastructure providers and energy companies.
- Discussion and strategic implications: The insufficient development of charging stations, particularly in non-urban areas and along highways, poses a significant technical barrier to EV adoption in Brazil.

The scarcity of charging points outside major cities creates "charging deserts," deterring potential EV buyers who require long-distance travel capabilities. This limitation directly impacts the INFR (Charging infrastructure deployment) variable, creating a chicken-and-egg problem where low EV adoption discourages infrastructure investment, and limited infrastructure hampers EV sales growth. The uneven distribution of charging stations also contributes to range anxiety among users, particularly for inter-city travel. Moreover, the lack of standardization in charging technologies and payment systems further complicates the user experience.

Overcoming this barrier requires coordinated efforts from charging infrastructure providers and energy companies, potentially supported by government incentives or public-private partnerships. Addressing this infrastructure gap is crucial for building consumer confidence and enabling the widespread adoption of EVs across Brazil's diverse geographical landscape.

**TB2 – Grid capacity constraints**

- Brief description: Existing power DNs may not be adequately prepared to handle increased demand from widespread EV adoption.
- Key variable: TRDI (T&D network effectiveness to handle EV charging demands)
- Key actors: Charging infrastructure providers and energy companies.
- Discussion and strategic implications: The existing power distribution networks in Brazil may not be adequately prepared to handle the increased demand from widespread EV adoption, posing a significant technical challenge.

This barrier directly impacts the T&D (T&D network effectiveness to handle EV charging demands) variable. As EV adoption scales up, the simultaneous charging of multiple vehicles, especially during peak hours, could strain local grids, potentially leading to power quality issues or even outages. The challenge is particularly acute in older urban areas or rural regions where infrastructure may be dated.

Moreover, the intermittent nature of renewable energy sources, which are increasingly part of Brazil's energy mix, adds complexity to grid management in the context of EV charging. Addressing this barrier requires substantial investment and strategic planning from energy companies and ANEEL to upgrade grid infrastructure, implement smart charging solutions, and develop advanced demand management systems. Failure to address these grid constraints could significantly impede the large-scale transition to EVs and potentially erode public confidence in electrification efforts.

**TB3 – Limited EV range and long charging times**

- Brief description: Current EV technology may not meet consumer expectations regarding driving range and charging speed.
- Key variables: AUTO (Vehicle autonomy for EVs), CHAR (Fuelling/Charging time).

- Key actors: Automotive manufacturers, and battery manufacturers.
- Discussion and strategic implications: Current EV technology often falls short of consumer expectations regarding driving range and charging speed, creating a significant barrier to widespread adoption. This limitation directly affects the AUTO (Vehicle autonomy for EVs) and CHAR (Fuelling/Charging time) variables. Many potential buyers, accustomed to the long ranges and quick refuelling times of ICE vehicles, find the current EV offerings inadequate for their needs, particularly for long-distance travel.

The perception of insufficient range, even if it exceeds daily driving requirements for most users, contributes to range anxiety. Additionally, long charging times, especially with lower-power charging options commonly available, can be a significant inconvenience compared to the quick refuelling of ICE vehicles. This barrier is particularly challenging in a country like Brazil with vast distances between major cities. Overcoming these limitations requires continued investment in battery technology and charging infrastructure from automotive manufacturers and battery manufacturers.

Advancements in fast-charging technologies and increased availability of high-power charging stations are crucial to aligning EV performance with consumer expectations and facilitating broader adoption.

### 4.8.3
### Economic barriers (EBs)

#### EB1 – High upfront costs of EVs

- Brief description: The initial purchase price of EVs remains significantly higher than comparable ICE vehicles.
- Key variable: COST (EVs ownership costs)
- Key actors: Automotive manufacturers, government and policymakers.
- Discussion and strategic implications: The significantly higher initial purchase price of EVs compared to equivalent ICE vehicles represents a major economic barrier to widespread adoption in Brazil. This directly impacts the COST (EVs ownership costs) variable. Despite potentially lower operating costs over the vehicle's lifetime, the high upfront investment often deters consumers, particularly in a price-sensitive market like Brazil.

The premium pricing is largely due to the high cost of battery technology and the current limited scale of EV production. This cost barrier is particularly challenging for middle and lower-income segments, potentially limiting EV adoption to more affluent consumers and exacerbating social inequalities in transportation.

The situation is further complicated by Brazil's high import taxes on vehicles and components, which can disproportionately affect EVs if there's limited domestic production. Overcoming this barrier requires concerted efforts from automotive manufacturers to reduce production costs, potentially through increased localization of manufacturing. Additionally, government intervention through targeted incentives, tax breaks, or subsidies could help bridge the price gap and make EVs more accessible to a broader range of consumers.

**EB2 – Uncertain resale value and vehicle lifetime**

- Brief description: Consumers may be hesitant due to uncertainty about EV resale value and overall lifespan.
- Key variable: LIFE (Vehicle lifetime).
- Key actors: Automotive manufacturers and financial institutions.
- Discussion and strategic implications: The uncertainty surrounding the resale value and overall lifespan of EVs creates significant hesitation among potential buyers in Brazil, directly impacting the LIFE (Vehicle lifetime) variable. Consumers, accustomed to the well-established resale market for ICE vehicles, face ambiguity when considering the long-term value retention of EVs. This uncertainty is compounded by concerns about battery degradation over time and the potential costs of battery replacement.

The rapidly evolving nature of EV technology also raises fears of premature obsolescence, where newer models with significantly improved capabilities could dramatically reduce the value of current EVs. Additionally, the limited historical data on EV performance and longevity in Brazil's specific climate and road conditions adds to this uncertainty. These factors collectively make it difficult for consumers to accurately assess the total cost of ownership, potentially deterring adoption.

Addressing this barrier requires collaborative efforts from automotive manufacturers to provide robust warranties and clear information about battery life and vehicle longevity. Financial institutions also play a crucial role in developing valuation models that accurately reflect EV depreciation, thereby facilitating more predictable resale markets and potentially offering more attractive financing terms.

#### EB3 – Limited financing options

- Brief description: Lack of tailored financial products for EV purchases may hinder adoption.
- Key variable: COST (EVs ownership costs).
- Key actors: Financial institutions, government, and policymakers.
- Discussion and strategic implications: The lack of tailored financial products for EV purchases in Brazil presents a significant economic barrier to adoption, directly affecting the COST (EVs ownership costs) variable.

Traditional auto financing models may not adequately account for the unique characteristics of EVs, such as higher upfront costs but potentially lower operating expenses. This gap in financing options can make EVs seem less accessible or financially viable to many consumers, even if the total cost of ownership over the vehicle's lifetime might be competitive with ICE vehicles.

The situation is exacerbated by potential hesitancy from financial institutions to offer competitive rates due to uncertainties about EV resale values and long-term performance. Moreover, the absence of innovative financing schemes, such as battery leasing options or EV-specific loan products that factor in fuel savings, further limits consumer choices. This barrier particularly affects middle-income consumers who might be interested in EVs but find the financing hurdles insurmountable.

Overcoming this challenge requires proactive engagement from financial institutions to develop EV-specific financing products, potentially supported by government incentives or guarantees. Collaboration between banks, automotive manufacturers, and policymakers is crucial to create a financing ecosystem that makes EVs more financially accessible to a broader range of consumers.

### 4.8.4. Social barriers (SBs)

#### SB1 – Public resistance to EV adoption

- Brief description: General scepticism or lack of awareness about EV benefits and performance.

- Key variable: PREF (Public preference towards light-duty EVs).
- Key actors: Consumers and environmental organizations.
- Discussion and strategic implications: General scepticism or lack of awareness about EV benefits and performance represents a significant social barrier to electrification in Brazil, directly impacting the PREF (Public preference towards light EVs) variable. This resistance often stems from misconceptions about EV capabilities, range limitations, and overall reliability.

Many consumers, accustomed to ICE vehicles, may harbour doubts about the practicality of EVs in their daily lives, particularly in a country with vast distances and diverse terrains like Brazil. The lack of firsthand experience with EVs contributes to this scepticism, as potential buyers may rely on outdated information or anecdotal evidence rather than current data on EV performance and benefits.

Additionally, concerns about the environmental impact of battery production and electricity generation may paradoxically discourage environmentally conscious consumers.

Overcoming this barrier requires comprehensive public education campaigns and increased opportunities for hands-on experience with EVs. Environmental organizations can play a crucial role in disseminating accurate information about the environmental benefits of EVs, while automotive manufacturers need to effectively communicate advancements in EV technology and performance. Addressing this public resistance is essential for creating a social climate conducive to widespread EV adoption in Brazil.

**SB2 – Range anxiety**

- Brief description: Fear of running out of battery power during long trips due to limited vehicle autonomy and charging infrastructure.
- Key variable: AUTO (Vehicle autonomy for EVs), INFR (Charging infrastructure deployment).
- Key actors: Consumers and charging infrastructure providers.
- Discussion and strategic implications: Fear of running out of battery power during long trips due to limited charging infrastructure is a significant psychological barrier to EV adoption in Brazil, affecting both the AUTO (Vehicle autonomy for EVs) and INFR (Charging infrastructure deployment) variables.

This anxiety is particularly acute in a country known for its vast distances between major cities and diverse geographical terrains. Even when the actual range of modern EVs is sufficient for most daily use, the perception of being stranded without a charging option can be a powerful deterrent for potential buyers.

This fear is exacerbated by the current scarcity of charging stations, especially along highways and in rural areas. The perceived inconvenience of planning trips around charging stops, coupled with concerns about charging time, further contributes to this anxiety.

Overcoming this barrier requires a two-pronged approach: improving EV range through technological advancements and significantly expanding the charging infrastructure network. Charging infrastructure providers play a crucial role in strategically deploying charging stations to create a sense of ubiquity and reliability. Additionally, clear communication from automotive manufacturers about real-world EV ranges and the development of user-friendly trip planning tools can help alleviate range anxiety and build consumer confidence in EV capabilities for long-distance travel.

**SB3 – Cultural attachment to ICE vehicles**

- Brief description: Strong cultural preference for traditional ICE vehicles, particularly in certain regions or demographics.
- Key variable: PREF (Public preference towards light EVs)
- Key actors: Consumers and automotive manufacturers.
- Discussion and strategic implications: A strong cultural preference for traditional ICE vehicles, particularly in certain regions or demographics of Brazil, presents a significant social barrier to EV adoption, directly impacting the PREF (Public preference towards light EVs) variable. This attachment is often rooted in longstanding traditions, perceptions of reliability, and emotional connections to the sound and feel of ICE engines.

Additionally, the association of certain vehicle types (like large SUVs or pickup trucks) with status or lifestyle may not yet have equivalent electric options in the Brazilian market. The familiarity and perceived robustness of ICE vehicles, especially in rural or challenging terrains, further reinforces this cultural attachment.

Overcoming this barrier requires a nuanced approach from automotive manufacturers to design EVs that resonate with Brazilian cultural preferences while highlighting the unique benefits of electric powertrains. Marketing strategies need to evolve to position EVs not just as eco-friendly alternatives but as technologically advanced, high-performance vehicles that enhance driving experiences. Engaging influential figures, from celebrities to respected industry leaders, in promoting EV adoption can also help shift cultural perceptions. Ultimately, addressing this cultural attachment is crucial for normalizing EVs in the Brazilian automotive landscape and accelerating their widespread adoption.

### 4.8.5 Industrial barriers (IBs)

#### IB1 – Limited domestic EV manufacturing capacity

- Brief description: Insufficient local production capabilities for EVs and their components.
- Key variable: SLAB (Skilled labour for EVs)
- Key actors: Automotive manufacturers, government and policymakers.
- Discussion and strategic implications: The insufficient local production capabilities for EVs and their components in Brazil presents a significant industry barrier, directly impacting the SLAB (Skilled labour for EVs) variable. This limitation hampers the country's ability to produce cost-competitive EVs at scale and creates dependency on imports, potentially leading to higher vehicle prices and limited model availability.

The lack of a robust domestic EV manufacturing ecosystem also means missed opportunities for job creation and economic growth in this emerging sector. Additionally, the absence of local production facilities can result in reduced customization of EVs for Brazilian market needs and preferences, potentially affecting consumer acceptance. The challenge extends to the production of critical components like batteries, where Brazil currently lags behind global leaders.

This gap in manufacturing capability also impacts the development of a skilled workforce familiar with EV technologies.

Overcoming this barrier requires significant investment in manufacturing infrastructure and technology transfer. Government and policymakers play a crucial role in creating incentives for both domestic and international manufacturers to establish EV production facilities in Brazil. Collaboration between automotive manufacturers, educational institutions, and government bodies is essential to develop the necessary skills and knowledge base for a thriving domestic EV industry.

**IB2 – Resistance from traditional auto industry**

- Brief description: Potential pushback from established ICE vehicle manufacturers and associated industries.
- Key variable: EVSH (EV share in LDV fleet %).
- Key actors: Automotive manufacturers and oil companies.
- Discussion and strategic implications: Potential pushback from established ICE vehicle manufacturers and associated industries in Brazil represents a significant barrier to EV adoption, affecting the EVSH (EV share in LDV fleet %) variable.

This resistance often stems from the substantial investments these companies have made in ICE technology and manufacturing facilities, creating a reluctance to rapidly transition to EV production. The shift to EVs requires significant retooling of production lines and retraining of workforce, which can be costly and time-consuming.

Additionally, the automotive supply chain, deeply entrenched in ICE vehicle production, may also resist change due to concerns about job losses or the need for substantial adaptation.

Oil companies, facing potential reduced demand for their products, may also indirectly influence the pace of EV adoption. This industry resistance can manifest in various ways, from lobbying against pro-EV policies to slow implementation of EV models in their product lines.

Overcoming this barrier requires a delicate balance of policy incentives and market pressures to encourage traditional manufacturers to embrace EV technology. Government policies that provide clear timelines for emissions reductions and incentives for EV production can help accelerate this transition. Collaboration between automotive manufacturers and emerging EV technology companies could also facilitate knowledge transfer and smoother industry transformation. Ultimately, addressing this resistance is crucial for leveraging the existing automotive industry infrastructure and expertise to accelerate EV adoption in Brazil.

**IB3 – Lack of skilled EV workforce**

- Brief description: Shortage of technicians and engineers trained in EV technology.
- Key variable: SLAB (Skilled labour for EVs)
- Key actors: Automotive manufacturers; research institutions and universities.
- Discussion and strategic implications: The shortage of technicians and engineers trained in EV technology presents a significant industry barrier in Brazil, directly impacting the SLAB (Skilled labour for EVs) variable. This skills gap spans various areas, from EV design and manufacturing to maintenance and repair.

The complexity of EV systems, including high-voltage batteries, electric motors, and advanced electronics, requires specialized knowledge that is currently scarce in the Brazilian labour market. This shortage can lead to higher costs for EV development, production, and maintenance, potentially slowing down the overall adoption rate.

The lack of skilled professionals also affects the ability of service centres to adequately maintain and repair EVs, which can erode consumer confidence in these vehicles. Also, the scarcity of EV experts in academic and research institutions limits the country's capacity for innovation and localized technology development in this field. Overcoming this barrier requires a coordinated effort between educational institutions, industry, and government. Universities and technical schools need to rapidly develop and implement EV-focused curricula and training programs. Automotive manufacturers play a crucial role in providing on-the-job training and collaborating with educational institutions to ensure that training aligns with industry needs. Government support through funding for education programs and incentives for workforce development in the EV sector is essential.

Addressing this skills shortage is critical for building a robust, self-sustaining EV ecosystem in Brazil, from manufacturing to long-term maintenance and innovation.

### 4.8.6 Environmental barriers (EnBs)

#### EnB1 – Concerns about battery production and disposal

- Brief description: Environmental impacts of battery manufacturing and end-of-life management.
- Key variable: RECY (Incentives for battery recycling/reuse)
- Key actors: Battery manufacturers, environmental organizations; environmental agencies; recycling and waste management companies.
- Discussion and strategic implications: Environmental impacts of battery manufacturing and end-of-life management present a significant barrier to EV adoption in Brazil, directly affecting the RECY (Incentives for battery recycling/reuse) variable. The production of Li-ion batteries, crucial for EVs, involves energy-intensive processes and the extraction of raw materials, which can have substantial environmental impacts.

These concerns can paradoxically discourage environmentally conscious consumers from adopting EVs. Additionally, the lack of a well-established battery recycling infrastructure in Brazil raises questions about the long-term sustainability of EV batteries.

The potential for improper disposal of end-of-life batteries poses risks of environmental contamination and resource waste. This issue is compounded by the current limited capacity for battery refurbishment or second-life applications in Brazil. The uncertainty surrounding battery longevity and replacement costs also contributes to consumer hesitation.

Overcoming this barrier requires a multi-faceted approach involving battery manufacturers, environmental organizations, and policymakers. Developing efficient, environmentally friendly battery production methods and establishing a robust recycling and repurposing ecosystem are crucial. Government incentives for battery recycling and clear regulations on battery disposal can help address these concerns. Public education on the overall life-cycle benefits of EVs compared to ICE vehicles is also essential. Addressing these environmental concerns is critical for ensuring that the transition to EVs genuinely contributes to Brazil's sustainability goals and maintains public support for electrification.

**EnB2 – Electricity grid relies heavily on fossil fuels**

- Brief description: The environmental benefits of EVs are limited if the electricity grid relies heavily on fossil fuels.
- Key variable: MATR (Incentive policies for cleaner electricity matrix)
- Key actors: Energy companies, government, and policymakers.
- Discussion and strategic implications: The environmental benefits of EVs are limited if the electricity grid relies heavily on fossil fuels, presenting a potential barrier to meaningful decarbonisation through EV adoption in Brazil. This issue directly impacts the MATR (Incentive policies for cleaner electricity matrix) variable. While Brazil has a relatively clean energy mix compared to most countries, thanks to its substantial hydroelectric capacity, there are still concerns about the carbon intensity of electricity generation, especially during dry seasons when thermal plants may be more heavily utilized. The perception that EVs might be powered by coal or diesel and contribute to increased emissions from electricity generation can dampen enthusiasm for EV adoption among environmentally conscious consumers.

Furthermore, the anticipated increase in electricity demand from widespread EV adoption could potentially lead to greater reliance on fossil fuel power plants if renewable energy capacity is not expanded correspondingly. This could create a scenario where the transition to EVs inadvertently increases overall carbon emissions. The challenge is compounded by the need for significant investment in grid infrastructure to support both increased renewable energy integration and the additional load from EV charging.

Overcoming this barrier requires a coordinated effort between energy companies and government policymakers to accelerate the transition to cleaner energy sources. This includes expanding solar, wind, and other renewable energy capacities, improving energy storage solutions to manage intermittency, and implementing smart grid technologies to optimize EV charging with renewable energy availability. Public education campaigns are also crucial to accurately communicate the emissions benefits of EVs in the context of Brazil's evolving energy mix. Addressing this challenge is essential to ensure that the electrification of transportation genuinely contributes to Brazil's climate goals and maintains public support for EV adoption.

## 4.9 Discussion

The five decarbonisation scenarios for the Brazilian LDV fleet by 2050 presented in this study present potential pathways for transport electrification in Brazil, along with associated challenges and opportunities. Comparing our results with previous studies reviewed in Chapter 2 reveals several significant contributions to the existing body of knowledge on vehicle electrification and decarbonisation scenarios.

By employing a prospective methodological approach and focusing on the unique Brazilian context, this dissertation expands upon and complements previous studies in several key areas. The conceptual framework presented in Chapter 3, combining foresight and forecast approaches, offers a more comprehensive conceptual framework compared to previous studies. While Silva (2011) and Raoofi et al. (2023) used morphological analysis, this study integrates this technique with detailed structural analysis and long-term scenario planning. This allows for a more holistic understanding of the complex interactions between key variables shaping the future of vehicle electrification.

Unlike global studies or those focused on other countries (such as van der Zwaan et al., 2013; Bramstoft and Skytte, 2018), this study specifically considers the Brazilian context, including the importance of ethanol in the country's energy matrix. Compared to work of Glyniadakis and Balestieri (2023), which also focused on decarbonisation of the LDV fleet in Brazil, this study makes several important methodological advancements and novel contributions, while building upon their foundation of exploring prospective decarbonization scenarios for Brazil's LDV fleet.

Methodologically, this dissertation employs a more comprehensive and sophisticated approach. While Glyniadakis and Balestieri primarily relied on emissions minimization algorithms and scenario modeling, this study integrates multiple methodological tools, including structural analysis, morphological analysis, and prospective scenario construction. The use of structural analysis, particularly through the MICMAC method, allows for a more nuanced understanding of the complex interrelationships between key variables affecting fleet electrification.

The morphological analysis employed in this dissertation represents a significant methodological advancement. By systematically exploring possible combinations of hypotheses, i.e., alternative variable states in morphological matrices, it allows for a more exhaustive and structured scenario development process. This approach enables the consideration of a wider range of potential futures and helps identify internally consistent scenarios, enhancing the robustness of the analysis.

Furthermore, by outlining trajectories for the periods 2025-2030, 2031-2040, and 2041-2050, this dissertation provides a more detailed view of the potential evolution of the sector than many previous studies. This temporal granularity allows for a clearer understanding of the inflection points and critical decisions that may shape the future of vehicle electrification in Brazil. which was not present in Glyniadakis and Balestieri's work.

In terms of contributions, while Glyniadakis and Balestieri focused primarily on the technical aspects of emissions reduction, this dissertation provides a more holistic view of the electrification landscape. The inclusion of 14 key variables spanning regulatory, economic, social, and environmental domains offers a more comprehensive understanding of the factors influencing fleet electrification.

Additionally, the identification and detailed analysis of 16 barriers to the implementation of light vehicle fleet electrification in Brazil represents a significant contribution. Previous studies, such as Costa et al. (2020) and Ruoso and Ribeiro (2022), addressed some barriers, but our analysis is more comprehensive and structured, categorizing barriers into regulatory, technical, economic, social, industrial, and environmental. This analysis provides actionable insights for policymakers and industry stakeholders, which were not as explicitly addressed in the previous work.

The dissertation also makes a unique contribution by developing a scenario (Scenario D) that specifically considers Brazil's strong position in ethanol production, integrating this aspect more deeply into the electrification strategy. This complements studies such as Glensor and Rosa (2019), which compared biofuel and electrification scenarios, and represents an advancement over Glyniadakis and Balestieri's more generalized scenarios.

While this study provides significant contributions, as mentioned so far, it is important to acknowledge its limitations to contextualize the findings and identify areas for future research. These limitations stem from methodological constraints, the scope of the study, and the inherent challenges of long-term forecasting in a rapidly evolving technological landscape, as follows:

- By concentrating only on the LDV fleet, our study does not address the important HDV sector, which is crucial for comprehensive transport decarbonisation. Future studies could expand this analysis to include all road transport segments;
- While this study offers quantitative projections for fleet composition and emissions reductions, it does not employ complex econometric models like some previous studies (e.g., Helgeson and Peter, 2019). The integration of more robust economic modeling could strengthen the quantitative projections.
- Although battery electric and plug-in hybrid vehicles were considered, we did not deeply explore the potential of emerging technologies such as FCEVs, which were considered in some previous studies (e.g., van der Zwaan et al., 2013), and the potential development of flex-fuel PHEVs in the Brazilian market.
- The present study does not provide a detailed analysis of the economic impacts of the transition to EVs, such as infrastructure costs or employment impacts. Future studies could incorporate more comprehensive economic analysis, as done by Broadbent et al. (2022) for the Australian context.

This study makes a significant contribution to the field of prospective scenario planning for vehicle electrification, particularly in the Brazilian context. By integrating foresight and forecast methodological approaches and by considering Brazil's unique context regarding biofuels, this study provides a foundation for future research and policy formulation.

The identified limitations also point to promising avenues for future research, including expanding the scope to other transport sectors, integrating more robust economic modelling, and deeper consideration of emerging technologies.

# 5
# Conclusion

This dissertation has explored the potential impact of electrification on decarbonisation scenarios for Brazil's LDV fleet by 2050, employing a hybrid methodological approach that combines foresight and forecast approaches.

Through the development and analysis of five distinct scenarios, ranging from low to high electrification and decarbonisation, this study contributes to the complex interplay of technological, economic, policy, and social factors that will shape the future of the LDV fleet in Brazil in this long-term horizon.

The research findings indicate that electrification has significant potential to enhance the decarbonisation of Brazil's LDV fleet, with estimated greenhouse gas emission reductions ranging from 7.0% in the least ambitious scenario to 25.7% in the most ambitious scenario by 2050. These results underscore the importance of electrification as a key strategy in Brazil's efforts to mitigate climate change and transition towards a more sustainable transportation system.

An important contribution of this study lies in its comprehensive consideration of Brazil's unique context, particularly its established ethanol industry. Scenario D, which combines moderate electrification with increased ethanol use (Scenario D), demonstrates a potentially effective pathway for Brazil to achieve a 21.3% reduction in emissions. This highlights the importance of leveraging existing strengths and resources in crafting tailored decarbonisation strategies.

The structural analysis conducted in this study revealed complex interdependencies among the key variables that influence the electrification process. Factors such as light-duty EV policy support, charging infrastructure deployment, and public preferences for light-duty EVs have emerged as critical drivers of change. This analysis provides policymakers and industry stakeholders with a nuanced understanding of where to focus their efforts on the maximum impact.

The identification and analysis of 16 barriers to implementing electrification, categorized into regulatory, technical, economic, social, industrial, and environmental domains, represent another significant contribution of this research. This comprehensive barrier analysis offers actionable recommendations for overcoming challenges in the transition to electric vehicles. Key barriers identified include the lack of clear ICE phaseout policies, high upfront costs of EVs, limited domestic EV manufacturing capacity, and concerns regarding battery production and disposal.

The study's methodological approach, combining structural analysis, morphological matrices, and forecasting techniques, offers a robust framework for exploring complex, long-term transitions in the light-vehicle fleet, with implications for the transportation sector in general. This approach allows for a more holistic consideration of potential futures than many previous studies, which incorporate both qualitative and quantitative elements to provide a rich, multifaceted analysis.

This study’s findings have several important policy implications. The significant variation in potential emission reductions across scenarios underscores the critical role of policy in shaping the future of vehicle electrification. Policymakers should consider establishing clear, long-term targets for EV adoption and ICE vehicle phaseout to provide certainty for the industry and consumers.

Given the multifaceted nature of the identified barriers, an integrated policy approach is necessary. This should encompass not only direct EV incentives but also policies to support charging infrastructure development, grid modernization, and workforce training.

Brazil's unique position as a major ethanol producer necessitates careful policy considerations to balance the promotion of vehicle electrification with continued support for the biofuel industry. Policies should aim to maximize the complementary potential of these technologies.

Policies to stimulate domestic R&D and manufacturing capabilities in EV technologies could help overcome barriers related to high costs and limited model availability, while also creating economic opportunities. Policymakers should consider implementing comprehensive public education campaigns regarding the benefits and practicalities of EV adoption to address social barriers.

The findings also suggest several key implications for industry stakeholders. Automotive manufacturers should develop robust strategies for transitioning their product lines and manufacturing capabilities to increase EV production considering the various scenarios presented.

Energy companies and infrastructure providers should accelerate investments in charging infrastructure, particularly in urban areas and along major highways, to support growing EV adoption of EVs.

Companies across the automotive and energy sectors should invest in training and reskilling programs to develop the workforce capabilities required for a more electrified transportation system.

The transition to EVs presents opportunities for innovative business models such as battery leasing or integrated mobility services, which companies should explore to overcome adoption barriers.

Companies in the automotive supply chain should assess and adapt their capabilities to meet the evolving needs of EV production, including the development of local supply chains for critical components.

Looking ahead, this research points to several important areas for future research and policy focus.

First, the development of a clear and ambitious policy framework to support EV adoption emerged as a crucial factor across all scenarios. This includes not only incentives for EV purchases, but also support for charging infrastructure development and grid modernization to handle increased electricity demand.

Second, the importance of developing domestic EV manufacturing capabilities is highlighted as a key factor in accelerating the adoption and maximizing economic benefits. This will require significant investment in research and development as well as workforce training to build the necessary skills base.

Third, the study underscores the need for a holistic approach to decarbonisation that considers the entire lifecycle of EVs, including battery production and end-of-life management. The development of a robust battery recycling and repurposing industry has emerged as a critical challenge and opportunity for Brazil.

Fourth, this research highlights the potential for innovative approaches that combine electrification with Brazil's strengths in biofuel production. Further exploration of technologies such as flex-fuel hybrid vehicles could offer a unique pathway for Brazil to leverage its existing infrastructure and expertise, while transitioning to a low-carbon transportation system.

Finally, this study emphasizes the importance of public engagement and education in driving the transition to electric vehicles. Addressing cultural attachments to traditional vehicles and alleviating concerns about EV performance and reliability will be crucial for accelerating adoption.

In conclusion, this dissertation provides a comprehensive and nuanced analysis of the potential for electrification to drive decarbonisation in Brazil's LDV fleet. By offering a range of scenarios and a detailed examination of key variables and barriers, it provides a valuable resource for policymakers, industry leaders, and researchers working towards a sustainable transportation future in Brazil. As the global community grapples with the urgent need to address climate change, studies such as this offer critical insights into the challenges and opportunities of transitioning to low-carbon transportation systems in diverse national contexts.

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# Appendix 1 - Brazilian policies associated with road transport and energy efficiency

Table A.1 – Brazilian policies associated with road transport and energy efficiency

| Policy | Year | Category | Description |
|---|---|---|---|
| PROCONVE - Programa de Controle de Emissões Veiculares | 1986 | Energy efficiency | The Vehicle Emissions Control Program (PROCONVE) aimed to reduce motor vehicle emissions to meet air quality standards, especially in urban centres. The Program promoted technology development to reduce pollutant emissions in vehicle and fuel production, as well as inspection and maintenance initiatives for vehicles in use. It also promoted awareness about air pollution caused by motor vehicles and established metrics to evaluate the results achieved. |
| CONPET - Programa Nacional de Racionalização do Uso dos Derivados do Petróleo e Gás Natural | 1991 | Energy efficiency | The National Program for Rationalization of the Use of Petrol and Natural Gas Derivatives (Conpet) promotes the rational use of fuels in all sectors. The main goals of the Program are to avoid waste in the use of oil, gas and derivatives; reduce harmful gas emissions; promote technology R&D; and offer technical support in energy efficiency (Eletrobras, 2019). |
| PEE/ANEEL - Programa de Eficiência Energética | 2000 | Energy efficiency | The Energy Efficiency Program (PEE) promotes energy efficiency by reducing energy waste and optimizing energy consumption in different sectors. According to the Ministry of Mines and Energy, it focuses on innovation and sustainability and has a selection process to identify projects based on their effectiveness and impact on energy efficiency. |
| PBE Veicular - Programa Brasileiro de Etiquetagem Veicular | 2008 | Energy efficiency | The Brazilian Program of Vehicular Labelling (PBE Veicular) measures, standardises and registers the energy efficiency level of LDVs. The Program helps to inform consumers about vehicles' efficiency, and promotes the manufacturing and sales of more efficient vehicles. Vehicles are classified into 15 categories, and labelled from "A" (most efficient) to "E" (least efficient). The label also contains information about vehicle autonomy in km/l, in the city and on the road, and $CO_2$ emissions in fossil fuelled vehicles (Eletrobras, 2019). In 2023, it has also added battery range to the labelling of BEVs and PHEVs (PNME, 2023). |
| PNEF - Plano Nacional de Eficiência Energética | 2008 | Energy efficiency | The National Energy Efficiency Plan (PNEf) guides energy efficiency policy in Brazil, estimating the electric energy potential for the country in the 2010-2030 period. The Plan establishes guidelines within the scope of the Procel and CONPET Programs, and assesses the importance of implementing measurement and verification methods in energy efficiency programs and projects. |
| PNMC - Política Nacional de Mudança do Clima | 2009 | Energy efficiency | The National Policy on Climate Change (PNMC) provides guidelines for the adaptation to adverse climate change effects on humans and the natural environment, as well as emissions reductions, climate change impact mitigation and to reduce vulnerability to the impacts (Lei Nº 12.187, de 29 de Dezembro de 2009). |
| PSTM - Plano Setorial de Transporte e de Mobilidade Urbana para Mitigação e Adaptação à Mudança do Clima | 2010 | Energy efficiency | The Transport and Mobility Sector Plan for Climate Change Adaptation and Mitigation (PSTM) is part of the National Policy on Climate Change. The Plan is reviewed every two years and the objective is to reduce carbon emissions in the sector through initiatives that lead to the expansion of freight transport infrastructure and the greater use of more energy-efficient modes and, in the urban mobility sector, the increased use of efficient public passenger transport systems. |

| Policy | Year | Category | Description |
|---|---|---|---|
| Inovar-Auto and Rota 2030 | 2011 | Manufacturing, taxation | The two Programs aim to stimulate the production of new technologies and promote efficient consumer habits on passenger and small cargo transport. After continuous growth since its inception in the 1950's, the Brazilian automobile industry somewhat fell behind in terms new technologies in the 2010's. Therefore, with Inovar-Auto in 2011, the government increased taxation on imported vehicles, while reducing it for domestic production, with a 30% difference between the two. In 2018, the Rota 2030 Program replaced Inovar-Auto, focusing on promoting R&D by providing tax credits to companies that invest in the area (Eletrobras, 2019). |
| PNMU - Política Nacional de Mobilidade Urbana | 2012 | Energy efficiency | The National Policy on Urban Mobility (PNMU) prioritizes active and public transport, as well as modal integration in urban transport. It stipulates that every municipality with a population of more than 20,000, needs to develop an urban mobility plan. The municipal plans need to follow the principles of the PNMU, integrating urban planning, social inclusion and environmental sustainability. |
| PNLI - Plano Nacional de Logística Integrada | 2012 | Energy efficiency | The National Plan of Integrated Logistics (PNLI) focuses on energy efficiency in freight transport by promoting technological and systemic efficiency, considering modal integration. The main objective of the project is to develop the strategic planning of freight transport by integrating railways, coastal and river shipping with road transport, the dominant mode in Brazil. |
| Resolução Normativa Aneel Nº 547/2013 | 2013 | Charging infrastructure | Establishes commercial procedures for the application of the tariff flag system in the electricity sector. The tariff flag system (green, yellow and red) aims to signal to consumers the real cost of generating electricity, allowing monthly tariff adjustments according to generation conditions (Resolução Normativa No 547, de 16 de abril de 2013). |
| Resolução Normativa Aneel Nº 733/2016 | 2016 | Charging infrastructure | Regulates the White Tariff, a tariff mode where the cost of electricity varies according to the time, with lower rates outside of peak hours and higher rates during periods of high demand, with the aim of encouraging consumption outside of peak hours. |
| Renovabio | 2016 | Energy efficiency | The National Biofuels Policy aims to expand the production of biofuels, based on predictability and environmental, economic and social sustainability, according to EPE. The program aims to improve policies and regulatory aspects of biofuels, in order to contribute to the solution of technical and economic challenges in the sector. |
| Programa de P&D/ANEEL | 2018 | Energy efficiency | ANEEL's R&D department started the program called "Desenvolvimento de Soluções em Mobilidade Elétrica Eficiente", with the objective of developing electric mobility solutions in the country. The project is not only focused on electrification but also in efficient urban and interurban mobility (Eletrobras, 2019). The program conducts research on impacts on the grid; development of component prototypes for EVs; development of charging infrastructure solutions; regulatory and commercial framework for successful electrification adoption; and integration with renewable sources, among other subjects related to electromobility. |
| Resolução Normativa Aneel Nº 819/2018 | 2018 | Charging infrastructure | The Resolution states that any interested party is allowed to carry out electric vehicle charging activities, including with commercial interests at free market prices. Local distributors can install charging stations in their area of operation for public charging of EVs. This was consolidated by Normative Resolution n. 1.000/2021, which consolidated the rights and duties of electricity consumers and establishes the rules for providing the public electricity distribution service (ANEEL, 2022). |

| Policy | Year | Category | Description |
|---|---|---|---|
| PPT- Políticas Públicas de Telecomunicações | 2018 | Charging infrastructure | The Public Telecommunications Policies (PPT) aim to: promote access to telecommunications under economic conditions that enable internet's use and services, including in underprivileged areas; provide a favourable environment for the expansion of telecommunications networks and the continuity and improvement of services provided; safeguard the rights of users; stimulate R&D; and stimulate constant technological updating of telecommunications services (IPEA, 2018). |
| Consulta Pública Nº 33/2017, Portarias Mme Nº 187/2019 E 403/2019 | 2019 | Charging infrastructure | The Public Consultation Nº 33/2017 and the Ministry of Mines and Energy's Ordinances Nº 187/2019 and 403/2019 established a working group to improve proposals that enable the modernization of the electricity sector, based on the pillars of governance, transparency and legal-regulatory stability, with topics such as: market environment and mechanisms for enabling the electricity sector's expansion, energy pricing, cost and risk allocation, sustainability of distribution services, among others, according to EPE. |
| Lgpd - Lei Geral de Proteção de Dados Pessoais | 2019 | Charging infrastructure | The General Personal Data Protection Law (LGPD) regulates the processing of personal data, with the aim of protecting freedom and privacy. It sets rules on the collection, processing, storage, and sharing of personal data, imposing administrative sanctions for violations. |
| Câmara das Cidades 4.0 | 2019 | Charging infrastructure | The Chamber of Cities 4.0 aims to increase the quality of life in Brazilian Cities through the adoption of technologies and practices that enable the integrated management of services for citizens and improvements in mobility, public safety and use of resources. It defines "smart cities" as committed to sustainable urban development and digital transformation in their economic, environmental, social and cultural aspects (MCTI, 2019) |
| Carta Brasileira para Cidades Inteligentes | 2020 | Charging infrastructure | The Brazilian Charter for Smart Cities defines the concept of "smart cities" as cities committed to sustainable urban development and digital transformation, in their economic, environmental, social and cultural aspects and act in a planned, innovative, inclusive and integrated way, promoting digital literacy, governance and collaborative management and use technologies to solve concrete problems, create opportunities, offer efficient services, reduce inequalities, increase resilience and improve the quality of life of all people, ensuring the safe and responsible use of data and information and communication technologies (Ministério das Cidades, 2021). |
| PNCI - Política Nacional de Cidades Inteligentes | 2021 | Charging infrastructure | The National Smart Cities Policy (PNCI) defines principles and guidelines for the development of smart cities in Brazil. It defines a smart city as an urban space directed to the investment on human and social capital, sustainable economic development, and the use of available technologies to improve and connect services and infrastructure in cities, in an inclusive, participative, transparent and innovative way (Lopes, 2022). |
| Programa Renovação De Frotas – Medida Provisória Nº 1.175/2023 | 2023 | Energy efficiency | The Fleet Renewal Program aims to promote the purchase of domestically produced vehicles with federal subsidies for "sustainable" vehicles in public fleets. It stipulates four criteria to evaluate the sustainability of a vehicle: energy source; energy efficiency; price; and density of domestically produced components. It attributed maximum points for electricity and ethanol as an energy source (PNME, 2023). |
| Mover – Mobilidade Verde e Inovação | 2024 | Manufacturing, taxation | The Green Mobility and Innovation Program (MOVER) builds on its two predecessors, the Inovar Auto and Rota 2030, by promoting investment in energy efficiency, stipulating minimum recycling rates and conceding tax breaks for entities that pollute less. The program considers energy emissions from well-to-wheel and stipulates cradle-to-grave emission standards from 2027. The tax incentive system also considers the energy source for propulsion; energy consumption; engine power; recyclability; and structural performance and driving assistance technology. |

Figure A.1 shows a timeline of policies related to energy efficiency in the road transport sector in Brazil. The first policies, starting with PROCONVE in 1986, focused on vehicle efficiency standards, until 2011 when an effort to start modernising the auto industry in the country started taking shape with Inovar Auto. From 2013 onwards there were a series of policies aimed at modernising the electricity sector that would have an impact on vehicle charging infrastructure and smart grids. The last significant policy was the Mover Program, announced in December 2023 as an evolution of Inovar Auto and Rota 2030, aiming to continue the modernisation of the auto industry, but also having energy efficiency elements related to carbon emissions.

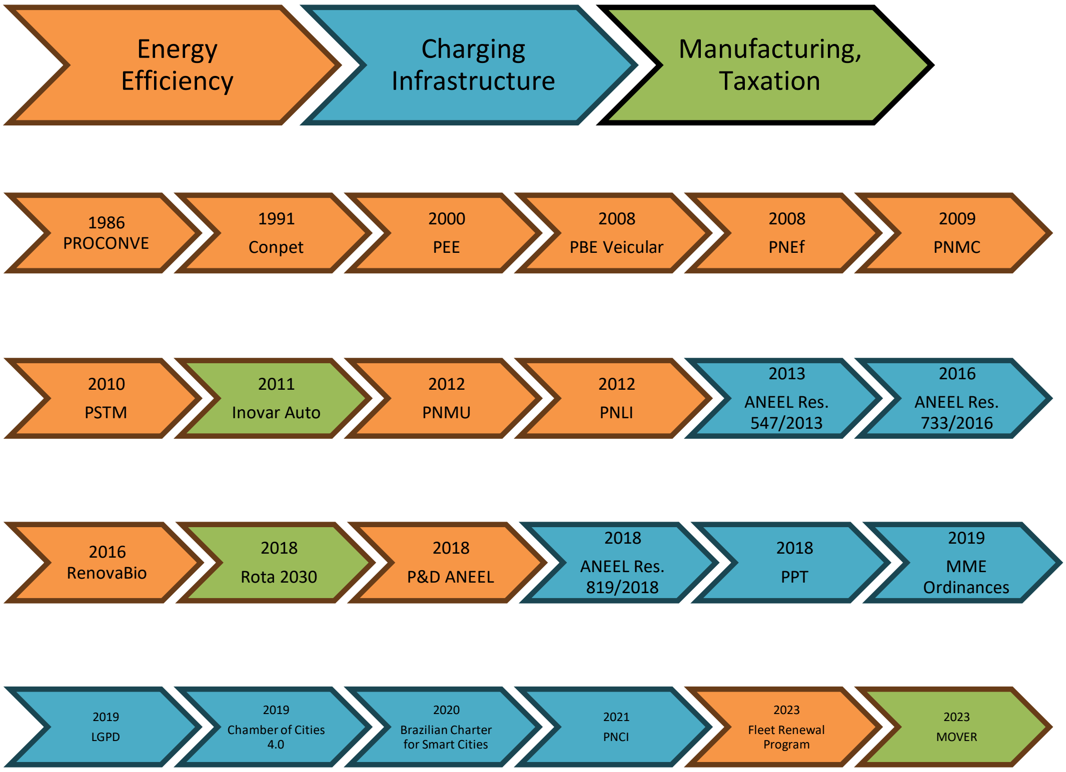


Figure A.1 – Timeline of energy efficiency policy in transportation

Other policies are under consideration in parliament, such as the National Policy on Electric Mobility (Política Nacional de Mobilidade Elétrica – PL nº 2156/2021). On its initial text, the initiative defines aspects such as electric mobility, EVs and charging stations and cites the electricity market, charging station operations and the operation of electric mobility networks as the main steps to support the energy transition. It also provides guidelines to encourage electrification such as regulation incentivising EV purchases, the development of a charging infrastructure network compatible with all EVs and regulation to encourage the installation of charging equipment in multifamily buildings. The Legal Framework for Collective Public Transport (Marco Legal do Transporte Público Coletivo) is another initiative being discussed. Although it does not specify transport electrification as a goal, it does provide guidelines for renewable energy sources to be used in public transport, and stipulates reducing emissions as one of the goals in public transport planning (PNME, 2023).

On the regional level, some municipalities have been introducing policies aimed at making EVs more convenient, facilitating charging infrastructure deployment, and decarbonising public transport and government fleets. Table A.2 lists and describes some municipal policies in effect or under consideration, aimed at transport electrification, and Table A.3 lists policies aimed at bus fleet electrification.

Table A.2 – Municipal policies aimed at transport electrification in Brazil.

| City | Policy | Description |
|---|---|---|
| São Paulo, SP | Lei nº 15.997/2014 | Low emission vehicles are excluded from the odd-even tag rotation in the city and suggests the possibility of exclusive traffic lanes for said vehicles. |
| Curitiba, PR | Decreto nº 588/2020 | Establishes a process for the permitting of DN and charging station installation projects in the public right-of-way. |
| Distrito Federal | PL nº 197/2023 | Concerning the obligation to provide solutions for the possible installation of charging equipment in residential and commercial buildings. |
| Distrito Federal | Decreto nº 43.056/2022 | Private parking lots or garages with more than 100 spots are obligated to dedicate at least 1% of the spots to EV charging. |
| São Paulo, SP | Lei nº 17.336/2020 | Mandate to residential and commercial building projects to provide solutions for the future installation of charging equipment. |
| São José dos Campos, SP | Lei nº 9.684/2018 | Authorises the municipality to establish policies aimed at encouraging EV adoption, including emissions reduction and fleet electrification targets for public transport and public services fleets. |

Source: PNME (2023).

Table A.3 – Municipal policies aimed at e-bus adoption

| City | Policy | Year | Goal |
|---|---|---|---|
| Several municipalities | E-bus tests | - | Pilot project to test e-buses in city routes |
| Several municipalities | Local climate Plans | - | Electric mobility related objectives in local plans |
| Volta Redonda | Zero Commercial Tariff | 2017 | E-bus purchases to operate around the main commercial centres in the city, free of charge |
| São Paulo | Lei 16.802 | 2018 | Target to reduce public transport vehicle $CO_2$ emissions by 50% in 10 years, and 100% in 20 years. |
| São Paulo | E-bus purchase and tests | 2019 | E-bus purchases for tests |
| Curitiba | Climate Action Plan – PlanClima | 2020 | Support the integration of strategies between sectors, aiming to reduce GHG emissions and improve climate change resiliency. |

| | | | |
|---|---|---|---|
| Curitiba | Sustainable Urban Mobility Program | 2021 | Renewal and enlargement of the e-bus fleet in two high-capacity lines |
| Salvador | E-bus purchases by the state government | 2022 | Replace part of the intercity bus fleet with e-buses |
| Salvador | BRT Salvador | 2022 | Electrification of the BRT system |
| São José dos Campos | Electric VLP | 2022 | Creation of an e-bus corridor |

Source: PNME (2023).

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