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Electric Mobility Contemplating Power Generation from Solar Photovoltaic

Nathalia Hidalgo Leite

Supervisor: Doctor Luiz Carlos Pereira da Silva
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Thesis approved in public session to obtain the PhD Degree in Electrical and Computer Engineering

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Jury

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Dedication

To my mother, for being my foundation and my greatest inspiration.

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Resumo

Com o aumento das emissões de gases de efeito estufa e o aquecimento global, as mudanças climáticas se tornaram um dos maiores desafios globais afetando ecossistemas, economias e sociedades. Esta tese aborda o cenário atual das mudanças climáticas e o papel fundamental das energias renováveis e dos veículos elétricos na mitigação de seus impactos. Fontes de energia renováveis são apresentadas como alternativas sustentáveis aos combustíveis fósseis, contribuindo para a redução das emissões de carbono e promovendo um modelo energético mais limpo e resiliente. Além disso, os veículos elétricos desempenham um papel essencial na descarbonização do setor de transportes, um dos maiores contribuintes para as emissões de gases de efeito estufa. Este documento discute a crescente adoção de sistemas solares fotovoltaicos, veículos elétricos e o uso combinado de energia renovável para recarga, considerando as regulações vigentes. O foco está na atratividade para adoção de tais tecnologias, analisando principalmente os aspectos econômicos. Três artigos são apresentados. O primeiro artigo analisa o impacto das regras brasileiras de *net-metering* nos investimentos solares fotovoltaicos, considerando a escala residencial. Os resultados mostram que da regra anterior (RN 482/2012) para a atual (Lei 14.300/2022) o retorno ao investidor, em média, diminuiu 5,77%. No entanto, essa redução seria de 12,81% se a regra considerada (AIR 003/2019) fosse adotada. Para os 36 estudos realizados, mesmo no pior caso os investimentos permanecem viáveis. O segundo artigo avalia a atratividade dos veículos elétricos em relação aos veículos de combustão interna para o Brasil, um país emergente com mercado consolidado de combustíveis alternativos e um sistema regulado de compensação de eletricidade. A partir dos 23 cenários analisados, conclui-se que veículos elétricos podem ser competitivos, em termos de custo, em relação aos veículos de combustão interna dependendo dos subsídios, da eficiência energética e do custo de aquisição dos veículos. O terceiro artigo avalia os efeitos dos mecanismos de compensação de energia no custo total de propriedade de veículos elétricos, também no contexto brasileiro. Os resultados mostram que partindo do cenário atual para qualquer outro cenário avaliado, a variação do custo total de propriedade de veículos elétricos é de no mínimo -1,8% e máximo 6,3%. Portanto, embora os efeitos dos mecanismos de compensação energética sejam mais significativos para os custos de energia e, em menor grau, para os custos anuais, no custo total de propriedade não atingem 7%.

Palavras-chave: Mudanças Climáticas, Transição Energética, Descarbonização, Viabilidade Econômica, Energia Solar, Mobilidade Elétrica.

Abstract

With increasing greenhouse gas emissions and global warming, climate change has become one of the greatest global challenges affecting ecosystems, economies, and societies. This thesis addresses the current climate change scenario and the key role of renewable energy and electric vehicles in mitigating their impacts. Renewable energy sources are presented as sustainable alternatives to fossil fuels, contributing to the reduction of carbon emissions and promoting a cleaner and more resilient energy model. In addition, electric vehicles play an essential role in the decarbonization of the transportation sector, one of the largest contributors to greenhouse gas emissions. This paper discusses the increasing adoption of solar photovoltaic systems, electric vehicles, and the combined use of renewable energy for recharging, considering current regulations. The focus is on the attractiveness for the adoption of such technologies, mainly analyzing the economic aspects. Three papers are presented. The first paper analyzes the impact of Brazilian net-metering rules on solar photovoltaic investments, considering the residential scale. The results show that from the previous rule (NR 482/2012) to the current one (Law 14.300/2022), the return to the investor, on average, decreased by 5.77%. However, this reduction would be 12.81% if the rule considered (RIA 003/2019) were adopted. For the 36 studies carried out, even in the worst-case scenario, investments remain viable. The second article evaluates the attractiveness of electric vehicles in relation to internal combustion vehicles for Brazil, an emerging country with a consolidated market for alternative fuels and a regulated electricity compensation system. Based on the 23 scenarios analyzed, it is concluded that electric vehicles can be cost-competitive in relation to internal combustion vehicles depending on subsidies, energy efficiency, and vehicle acquisition cost. The third article evaluates the effects of energy compensation mechanisms on the total cost of ownership of electric vehicles, also in the Brazilian context. The results show that, starting from the current scenario for any other scenario evaluated, the variation in the total cost of ownership of electric vehicles is at least -1.8% and a maximum of 6.3%. Therefore, although the effects of energy compensation mechanisms are more significant for energy costs and, to a lesser extent, for annual costs, they do not reach 7% in the total cost of ownership.

Keywords: Climate Change, Energy Transition, Decarbonization, Economic Viability, Solar Energy, Electric Mobility.

Summary

1 - INTRODUCTION

Climate change represents one of the greatest contemporary global challenges with profound impacts on natural and human systems. Global warming, driven primarily by greenhouse gas emissions, has generated adverse effects on the earth, such as the intensification of extreme weather events. The main cause of this phenomenon is the burning of fossil fuels, which contribute to the increase of greenhouse gases in the atmosphere (UN, 2025).

The case for action has never been stronger. The United Nations Climate Change Conference – Dubai/2023 (COP 28) marked the conclusion of the first global stocktake of the world's efforts to address climate change under the Paris Agreement. The decision highlights the urgency to accelerate global efforts towards climate neutral energy systems (UNFCCC, 2025).

In this context, energy transition emerges as a central component in mitigating the effects of climate change. Energy transition refers to the shift from an energy matrix dependent on non-renewable sources to a model based on renewable and clean energy. This process aims to reduce greenhouse gas emissions, improve energy efficiency, and promote energy security (UNDP, 2025).

Among the renewable energy sources, solar energy stands out as one of the most promising. The use of solar radiation to generate electricity offers a clean, abundant, and affordable solution with the potential to significantly reduce dependence on fossil fuels. Photovoltaic technology, in particular, has developed rapidly providing greater efficiency and cost reduction. In addition, solar energy has the advantage of being decentralized, allowing remote regions to benefit from this renewable energy source. Many countries, such as Brazil, have supported solar energy through policies (IEA, 2025).

The transport sector is one of the largest sources of greenhouse gas emissions, mainly due to vehicles' dependence on internal combustion engines that burn fossil fuels, such as gasoline and diesel. CO_2 emissions from vehicles directly contribute to the increase in the concentration of gases in the atmosphere, resulting in global warming. Replacing internal combustion vehicles with electric models has the potential to substantially reduce emissions of CO_2 and other air pollutants, especially in urban areas.

Furthermore, electric vehicles represent an opportunity for innovation in the transportation sector, with advances in battery technologies, improvements in charging infrastructure, and the strengthening of public policies that encourage their adoption. The growing popularity of electric vehicles can also contribute to the diversification of the energy matrix, since they can be powered by clean energy sources, such as solar and wind (IPCC, 2025).

This thesis is presented as a collection of three papers, mainly focused at economic aspects of investing in technologies, such as solar energy and electric mobility, considering the need for energy transition in order to mitigate climate change. The first paper is entitled "*Impact of the net-metering policies on solar photovoltaic investments for residential scale: A case study in Brazil".* The objective of the study is to analyze how energy compensation mechanisms impact photovoltaic investments, considering the investor's point of view. A mathematical model of discounted cash flow is developed in order to calculate discounted payback, net present value, internal rate of return, and levelized cost of energy for solar photovoltaic investments.

The second paper is entitled "*Electric vehicles attractiveness in emerging country (Brazil) considering policy and regulation towards energy transition".* The objective of this research is to study how financially smart are electric vehicles (hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles) relative to internal combustion vehicles. A mathematical model is developed to calculate the total cost of ownership in net present value, considering biofuels and net-metering.

The third paper is entitled "*Energy compensation mechanisms (net-metering) and their effects in the total cost of ownership of electric vehicles*". The objective is to understand how net-metering rules affect the total cost of owning electric vehicles. The photovoltaic regulation presented in the first paper and the mathematical model developed in the second paper were employed in this research. Therefore, as Figure 1, the third paper derives from a combination of the first two.

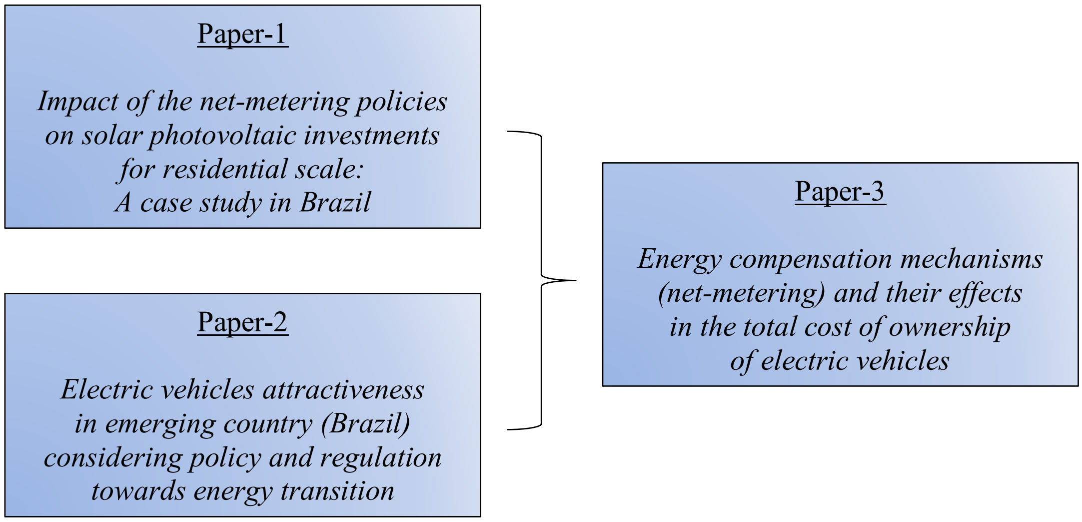

Figure 1 – Papers attached to the thesis

As a collection of papers, the organization of this thesis follows an alternative structure stablished by the "*Instrução Normativa - Comissão Central de Pós Graduação (CCPG)*" nº 002/2021. According to this normative instruction, the thesis should contemplate five chapters, presented in this document as follows. Chapter 1-Introduction describes the context of the research and the papers that comprehend the thesis. In chapter 2-Documents, the three papers previously mentioned are attached. In chapter 3-Discussion, there is an analysis of the findings of each paper. In chapter 4-Conclusion, the key takeaways are presented. Chapter 5-References lists the bibliographical material cited in the Introduction and Discussion chapters of this thesis.

2 - DOCUMENTS

2.1 - Impact of the Net-Metering Policies on Solar Photovoltaic Investments for Residential Scale: A Case Study in Brazil

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Impact of the net-metering policies on solar photovoltaic investments for residential scale: A case study in Brazil

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Abstract

The adoption of renewable energy resources is in the core of energy transition. However, its implementation can be highly impacted by country policies. A limited number of researches investigated solar photovoltaic investments, comparing net-metering rules for distinctive energy consumption levels and different discounted rates, from the investors' point of view. This paper analyzes the impact of Brazilian net-metering rules on solar photovoltaic investments, considering residential scale. The methodology contemplates the development of a Discounted Cash Flow model to calculate Discounted Payback (DP), Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Electricity ($LCOE$) of projects. The case studies consider the impact of Brazilian regulation from net-metering rules (previous, considered, and current), energy consumption levels (Low, Middle, and High), and discount rates (5%, 10%, 15%, and 20%). The results show that from the previous to current rule the return for investor, on average, decreased 5.77%. However, this reduction would be of 12.81% if considered rule was adopted. For the 36 studies carried out, even in the worst case the investments remain viable. Therefore, the existing policy is suitable for the current stage of sector development; minimizing the impacts for energy tariff, distribution companies, consumers, and prosumers.

Keywords
Compensation Mechanism, Distributed Generation, Economic Viability, Legal Framework, Regulatory Policy, Solar Energy.

List of variables

CF_n	Cash flow in the period n [R$]
C_n	Photovoltaic system costs in the period n [R$]
DCF_n	Discounted cash flow in the period n [R$]
DP	Discounted payback [years]
En	Energy generated by the photovoltaic system in the period n [kWh]
IRR	Internal rate of return [%]
$LCOE$	Levelized cost of electricity [R$/kWh]
n	Period or year of the DCF
n_{esp}	Smallest value of n for positive accumulated DCF
NPV	Net present value [R$]

List of parameters

Ger_n	Average generation in the year n, considering surplus compensation [kWh]
I_0	Initial investment cost [R$]
$MARR$	Minimum attractive rate of return [%]
N	Number of periods considered
$O\&Mn$	Cost of maintenance and insurance of the system in the year n [R$]
r	Discount rate [%]
$Tarn$	Average energy tariff in the year n [R$/kWh]
α	Degradation rate of the photovoltaic system [%]
β	Readjustment rate of the energy tariff [%]
γ	Readjustment rate of the $O\&M$ costs [%]

1. Introduction

Distributed Generation (DG) using solar Photovoltaic (PV) increased 26% worldwide in 2022. This was the largest absolute generation growth of all renewable sources in the year. Wind generation was surpassed for the first time in history. Some factors that contributed to this expansion include: development of the supply chain, increase in the economic attractiveness, and policy support. Policy support remains as the main driver for PV deployment in the world (IEA, 2023).

DG refers to technologies that generate electricity at or near the place it is used. The distributed system may serve a single structure, as a home, or it may be part of a microgrid (smaller grid connected to a larger electricity delivery system), as an industrial facility. DG allows for reduction in transmission and distribution lines losses, improvement in grid stability/security, and reduction in the environmental impact of electricity generation. In the residential sector, common DG systems include solar PV and small wind turbines (EPA, 2024).

Solar PV uses cells to convert light from the sun in electricity. The PV cell consists of one or two layers of a semi conducting material, usually silicon. When the light strikes the cell, it creates an electric field across the layers causing electricity to flow. More light intensity results in greater flow of electricity. The basic component of solar PV technology is the cell. Multiple PV cells are connected to form a PV module or panel - the smallest PV component sold commercially. PV modules or panels can be arranged in groups to form a PV array (EERE, 2024).

There are three main types of solar PV systems: on-grid, off-grid, and hybrid. The on-grid systems are connected to the public electricity grid. These are the most common systems used by residential consumers. An off-grid system is not connected to the electricity grid and, therefore, it requires battery storage. The use cases include rural and remote areas. Hybrid systems are dependent on the grid and can also accumulate extra electricity in a storage unit. These are more suitable for the agricultural or residential sector (WEC, 2019).

The introduction of DG using solar PV systems connected on-grid creates a new relational structure between consumers and distribution companies - the flow of power becomes bidirectional. This results in challenges in grid management and control. The main point of concern is related to how consumption and generation flows are measured and billed, that is, what compensation mechanism is used. According to NREL (2017), compensation mechanisms are defined as a reward to DG system owners for the electricity they self-consume and the excess that is exported to the grid.

NREL (2017) affirms there are effectively three types of compensation mechanisms: net-metering, buy-all sell-all, and net-billing. In the net-metering mechanism, a consumer installs small generators in their residence, such as solar PV or wind turbine, and the energy generated is used to offset the unit's electricity consumption. When generation is greater than consumption, the positive energy balance can be used to reduce consumption in subsequent months. There is also the possibility for the consumer to use surplus generation in other units previously registered within the same distribution area (ANEEL, 2023a).

In a buy-all sell-all mechanism, DG system owners buy all electricity from a company to consume and sell all electricity produced by their system. There is a standard sell rate for the electricity generated. In net-billing mechanism, DG system owners can consume electricity generated by their system in real time and export any generation in excess to the grid. However, different from net-metering, saving kilowatt-hours within a billing cycle to offset future consumption is not allowed. All net energy exported is metered and credited at a predetermined sell rate at the moment it is injected into the grid (NREL, 2017).

In Brazil, the compensation mechanism for DG systems is defined by the Brazilian Electricity Regulatory Agency (acronym in Portuguese, ANEEL). This organization is an independent federal agency in charge of supervising and regulating the electricity sector. Through Normative Resolution nº 482/2012, ANEEL regulated the net-metering, called Electric Energy Compensation System (EECS) in the country (REN, 2012).

In the last decade, solar PV has increased exponentially in Brazil. Figure 1 shows the evolution of solar PV installed power from Normative Resolution nº 482/2012 that allowed Brazilian consumers to generate their own electrical energy from renewable sources. According to Hansen & Zambra (2020), the exponential growth of the solar PV in Brazil can be justified by incentive policies, stimulus for acquisition, and falling price of equipment. Other factors, such as rise in electricity tariff, can also contribute to solar PV adoption. Among incentive policies, net-metering is implemented in Brazil and it is the most adopted globally (Komeno et al., 2022). As stimulus for acquisition in the country, facilitated credit lines that aim to mitigate climate change, such as Climate Fund, can be cited (BNDES, 2024). Lastly, falling price of equipment due to drop in prices of key materials (as polysilicon) has favored the expansion of the solar source, as documented by NREL (2021).

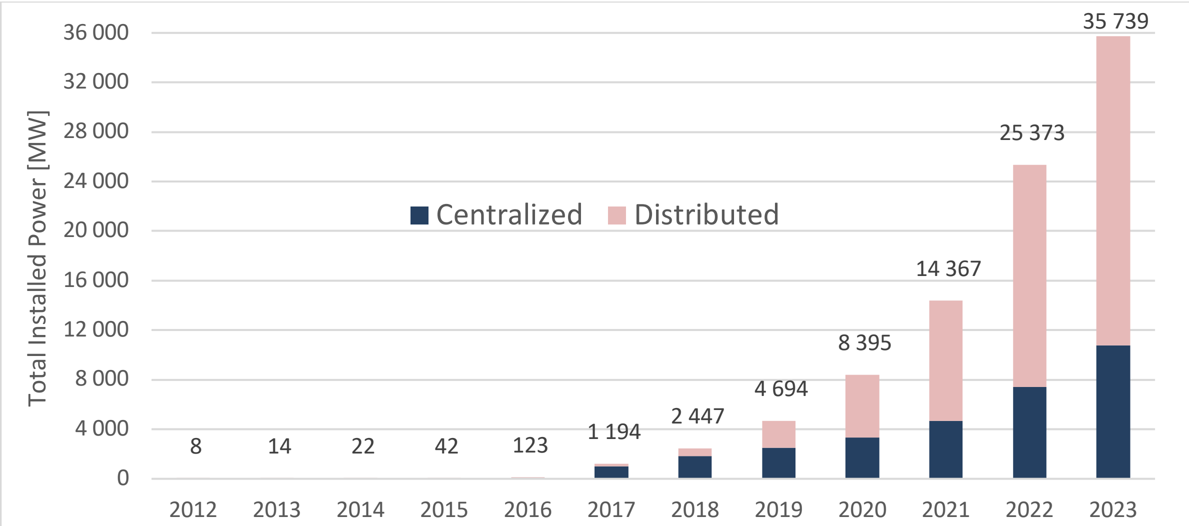


Figure 1 - Evolution of the PV Installed Power in Brazil from 2012 (ANEEL, 2023b)

It is important to maintain growth of solar PV since the technology presents significant benefits to the environment and society in general. Solar PV contributes to the reduction of greenhouse gases emissions (i.e. decarbonization), allowing for deceleration of global warming (i.e. climate change). This is crucial especially for the 140 countries that have committed to net-zero target in Paris Agreement (UN, 2024). Moreover, DG from solar PV is an alternative for energy generation that implies lower investments on grid because it supplies local energy demand. Thus, it significantly impacts countries with emerging economy, such as Brazil, with large distances and absent or weak grid where it is expensive to extend or improve outdated transmission and distribution lines (GSC, 2022).

However, the fast penetration of solar PV creates complex scenarios, especially related to regulation. Net-metering rules impact PV system owners, non-PV system owners, and distribution companies. Under compensation can shift additional costs to PV system owners. Over compensation implies a loss of revenue for the distribution companies, transferring electricity costs for non-PV system owners. According to Iglesias & Vilaça (2022), this may contribute to increased social inequality. The challenge is to create a model that results in a fair billing mechanism for participants while guaranteeing the growth of solar sector.

Therefore, the main motivation of this paper is the fact that net-metering rules affect attractiveness of solar PV investments. These rules can encourage or discourage solar PV adoption, altering pace for energy transition. Thus, understanding how profitability of solar PV investments is impacted by the compensation mechanisms is crucial for countries' sustainable development.

The expansion of solar PV led to numerous studies focused on net-metering in many countries, such as China (Jia et al., 2020), United States (Gazmararian & Tingley, 2024), Japan (Yang et al., 2024), India (Kaur & Kaur, 2023), and Germany (Sarfarazi et al., 2023). A review on solar energy policy for all of these countries was presented in Minazhova et al. (2023). Considering the topics “net-metering”, “solar photovoltaic”, and “Brazil”; in the last five years the following authors published their findings: Vieira & Carpio (2020), Drumond Jr. et al. (2021), Santos & Lucena (2021), Costa et al. (2022), Iglesias & Vilaça (2022), Komeno et al. (2022), and Pinto et al. (2024).

Santos & Lucena (2021) evaluates the influence of climate change on the technical-economic potential of PV systems in the residential sector. Pinto et al. (2024) assesses the benefits of a battery energy storage system on the financial attractiveness of PV generation in public buildings. Although these two studies evaluate the economic viability of PV investments and are related to net-metering, their focus is not towards compensation mechanism.

Vieira & Carpio (2020) analyzes the economic impact on residential fees under transition to distributed PV systems connected to grid. Komeno et al. (2022) explores the economic impact of net-metering rules for solar PV systems. Costa et al. (2022) presents the socioeconomic and environmental consequences of the current compensation rule in 35 Brazilian concession areas. These three studies are focused on the impact of net-metering on PV systems. However, their point of view is for non-PV adopters and/or distribution companies.

Drumond Jr. et al. (2021) investigates the impact of fiscal and tariff incentives on the economic viability for a residential PV system in 35 distribution companies. Iglesias & Vilaça (2022) studies the effect of the previous and current net-metering rules on technical-economic aspect of PV systems. The first one applies DP and NPV; while the second employs DP, $LCOE$, and cost/benefit. Both of them perform assessments for a single discount rate and energy consumption characteristic.

Therefore, although the impact of the net-metering rules on solar PV projects has been the subject of these studies, there is a gap in further evaluating diverse scenarios in the Brazilian context from the PV system owner's point of view. As an example, the application of viability indicators and variation of discount rates and energy consumption levels have been neglected in previous studies. Diverse scenarios can provide broader information on the topic, resulting in better fitting within the global context for adequate comparisons or implementations for countries with objectives similar to Brazil (of reducing incentives as solar PV installed capacity becomes more substantial). Besides, wider coverage benefits scientific community, as well as, policy makers, regulatory agencies, and end consumers supporting their decision-making.

Brazil is an important case study for several reasons. According to ANEEL (2023b), almost 85% of Brazil's electrical matrix comes from renewable sources. This makes the country stand out as an international reference. In 2023, Brazil placed the 6th country in the world rank in terms of solar energy capacity after China, United States, Japan, Germany, and India (IRENA, 2024). Its geographical location (almost entirely within the tropical zone) allows for high solar irradiation, with a daily incidence that can range from 4,500 to 6,300 Wh/m². This contributes to great potential for solar PV in the country (Atlas, 2017).

In this circumstance, and considering the climate change discussions that drive energy transition, this paper evaluates the impact of the net-metering policies on PV investments. The main EECSs presented in Normative Resolution nº 482/2012, Regulatory Impact Analysis nº 003/2019, and Law nº 14.300/2022 (previous, considered, and current) are investigated. Their influence is analyzed from the investor's point of view, considering residential units with different levels of consumption (Low, Middle, and High). The methodology is based on the creation of a discounted cash flow model and four economic and financial viability indicators (PD, NPV, IRR, and $LCOE$), covering discounted rates appropriate to the country's economic indices (5%, 10%, 15%, and 20%). In total, 36 scenarios are examined.

The main contributions from this paper contemplate: (i) a mathematical model for evaluating the economic viability of solar PV investments, from PV system owners' point of view, that can be adapted and employed worldwide; (ii) a historical background that describes the evolution of solar PV regulation in Brazil; (iii) a detailed analysis of the impact of different net-metering rules for solar PV attractiveness based on Brazilian experience; and (iv) a full exploration of the variation of PD, NPV, IRR, and $LCOE$ for 36 investigated scenarios that includes different discount rates and consumption levels which have shown significant impact on results.

The remainder of this article is structured as follows: Section 2 describes the background information on the PV regulation. Section 3 shows the development of the mathematical model employed. Section 4 presents the data of the consumer units, PV systems, scenarios, and model parameters. Section 5 shows the results and discussion considering different consumer units projects, discount rates, and net-metering policies. Finally, Section 6 brings key findings, comparison with previous studies, and economic/policy/social implications. Lastly, Section 7 presents conclusions, limitations, and future works.

2. Background

The policy related to DG has gone through numerous modifications in Brazil. The regulation started with the publication of Normative Resolution nº 167/2005 which established conditions for purchasing and selling energy (REN, 2005). Then, Normative Resolution nº 414/2010 (updated by Normative Resolution nº 1000/2021), among other things, defined rights and duties of consumers and distributors (REN, 2010). After that, several Public Consultations, Public Hearings, Normative Resolutions, Regulatory Impact Analysis, Law Projects, and Laws were published in order to adjust rules.

Public Consultation nº 15/2010 and Public Hearing nº 42/2011 were held to discuss a legal provision, seeking to reduce barriers for installation of DG systems. The result was Normative Resolution nº 482/2012 that defined the Electric Energy Compensation System (EECS) and Micro and Mini Distributed Generation (MMDG). The EECS is as an arrangement in which the energy injected by a consumer unit with MMDG is transferred as a free loan to the local distributor and subsequently compensated with its own electrical energy consumption. The MMDG was established as microgeneration systems up to 100kW and minigeneration systems from 100kW to 1MW (REN, 2012).

Normative Resolution nº 482/2012 established a revision process. The new versions were Normative Resolution nº 517/2012, nº 687/2015, and nº 786/2017. Normative Resolution nº 517/2012 essentially changed legal aspects related to the energy transfer from the consumer to the grid. Normative Resolution nº 687/2015 and nº 786/2017 mainly aimed to improve topics related to the installed power limits and the modalities of participation (REN, 2012).

Normative Resolution nº 687/2015 changed the power limit of microgeneration for up to 75 kW and of minigeneration for greater than 75kW and less than or equal to 3 MW for hydraulic sources and up to 5 MW for other renewable sources. Furthermore, new modalities for participation in the EECS were created in addition to local self-consumption: multiple consumer units, shared generation, and remote self-consumption. Normative Resolution nº 786/2017 changed the minigeneration to greater than 75kW and up to 5 MW and prohibited the inclusion of existing generating plants in the EECS (REN, 2015; REN, 2017).

The most updated regulation, Normative Resolution nº 1059/2023, revokes Normative Resolution nº 482/2012, nº 517/2012, 687/2015, and 786/2017. As can be observed, the revisions did not change the net-metering in terms of compensation. However, this was the most critical point to be altered. Therefore, the Brazilian Electricity Regulatory Agency (ANEEL) published two documents with suggestions for alteration: Regulatory Impact Analysis nº 0004/2018 and nº 003/2019. In 2022, with the creation of the Law nº 14.300/2022 based on Law Project nº 5829/2019 a partial compensation mechanism was established (NT, 2018).

In order to understand the net-metering in Brazil, it is important to describe the structure of the electricity tariff. The electricity tariff is composed by two main parts called: Distribution System Use Tariff (TUSD) and Energy Tariff (TE). Table 1 shows each component of the electricity tariff used by ANEEL in Technical Note nº 0062/2018 (NT, 2018).

TUSD represents around 50% of the total electricity tariff. It refers to the remuneration of the transmission and distribution utility companies and it is formed by four components. Distribution Line (28%) represents regulatory costs for the use of assets of the distribution companies. Transmission Line (6%) consists of regulatory costs for the use of assets of the transmission companies. Charges (8%) characterizes the costs related to the electricity distribution service. Losses (8%) recovers network costs with technical and non-technical losses (GIZ, 2019).

TE is responsible for the other 50% of electricity tariff. It corresponds to the charges for the energy consumed in the month. TE is formed by two components. Charges (12%) represents costs of service, reserved energy (that ensures the supply of energy to the National Interconnected System), and contribution on the use of water resources (which is legal obligation of producers of electricity from water sources). Energy (38%) recovers the costs of purchasing electricity for resale to the consumer (GIZ, 2019).

Table 1 - Components of the electricity tariff and average percentage weight

Distribution System Use Tariff (TUSD)				Energy Tariff (TE)	
Distribution Line 28%	Transmission Line 6%	Charges 8%	Losses 8%	Charges 12%	Energy 38%

It is important to note that the percentages listed in Table 1 are average values. The value of Distribution Line, for example, is calculated according to the local power distribution company and number of consumers served by the company in the area. For some entities, such as Greener, Distribution Line is equal to 30.8% (Greener, 2023).

EECS alternatives are distinguished by the way they value the energy injected into the grid. The regulation established by Normative Resolution nº 482/2012 determined that all components of the electricity tariff are considered. In this case, 100% of the energy injected is compensated. This means that 1 kWh of energy injected into the grid would generate 1 energy credit (REN, 2012).

The rule proposed by ANEEL in Regulatory Impact Analysis nº 003/2019 would compensate only one part of the electricity tariff, TE Energy. For this situation, approximately 38% of the energy injected would be compensated (AIR, 2019).

Lastly, Law nº 14.300/2022 is structured depending on the date the consumer joined the EECS, as follows (Law, 2022):

- before 2023: all electricity tariffs are compensated until 2045.
- from 2023 to 2028: seven years of gradual payment (15%-90%) of the TUSD Distribution Line - 28% (that corresponds to around 100% - 28% = 72%).
- after 2029: compensation will be defined by ANEEL after valuing the benefits of DG.

The net-metering presented in Normative Resolution nº 482/2012 (EECS = 100% compensation), Regulatory Impact Analysis nº 003/2019 (EECS = 38% compensation), and Law nº 14.300/2022 (EECS = 72% compensation) are investigated in this research. They correspond to the previous, considered, and current EECS in Brazil.

3. Methodology

Usually, the economic consideration of a project is based on the expected financial return on the investment. Economic engineering deals with the main methods used to analyze investment projects. Therefore, it helps decision-making about investment alternatives. Since this research considers the time value of money, the concept of Discounted Cash Flow (DCF) is applied. In this case, the estimated Cash Flows (CFs) are discounted at a rate, r [%]. The objective is to bring the nominal values of each period to the present, according to Equation (1).

For r, the country's main economic indices, such as national consumer price index and general market price index can be employed. DCF_1, DCF_2, ..., DCF_N correspond to the present value of CF_1, CF_2, …, CF_N; respectively. N is the total number of periods and n is the specific period considered (Park, 2019).

$$DCF_n = \frac{CF_n}{(1+r)^n} \quad (1)$$

DCF is widely used to evaluate projects, assets or companies. Therefore, it is the basis for decisions of investment, acquisition or business merger. All viability indicators that use the DCF require an accurate estimate of future CFs.

The methodology includes the development of a mathematical model to calculate the viability indicators of solar PV investments. Among the indicators, the following stand out: Discounted Payback (DP), Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Electricity ($LCOE$).

3.1 Viability indicators

Discounted Payback (DP)

DP is used to calculate the number of periods (years, months, weeks, etc.) required for a project to return the initial capital invested (Newman, et al., 2020). It corresponds to the value of n (specific period) when the sum of the $DCFs$ is equal to the value of the initial investment, I_0 or DCF_0, as Equation (2).

$$\sum_{n=1}^{DP} DCF_n = |DCF_0| \quad (2)$$

The lower the DP, the more liquid the investment and therefore less risky. This indicator considers the time value of money, but does not consider the CFs after the payback period. DP can be obtained according to Equation (3), where n_{esp} corresponds to the smallest value of n for positive accumulated DCF.

$$DP = (n_{esp} - 1) + \frac{\left|\sum_{n=0}^{n_{esp}-1} DCF_n\right|}{\left|\sum_{n=0}^{n_{esp}-1} DCF_n\right| + \sum_{n=0}^{n_{esp}} DCF_n} \quad (3)$$

For example, for an initial investment of R$ 50,000.00, with constant annual return of R$ 14,000.00, and discount rate equal to 10%; Table 2 shows CF, DCF, and accumulated DCF, considering 10 years. According to this table, the invested capital will be returned between the fourth and fifth years (in blue on the table), more specifically, in 4.65 years (calculated in the sequence).

Table 2 - CF, DCF, and accumulated DCF

Year	CF	DCF (10%)	accumulated DCF
0	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00
1	R$ 14,000.00	R$ 12,727.27	-R$ 37,272.73
2	R$ 14,000.00	R$ 11,570.25	-R$ 25,702.48
3	R$ 14,000.00	R$ 10,518.41	-R$ 15,184.07
4	R$ 14,000.00	R$ 9,562.19	-R$ 5,621.88
5	R$ 14,000.00	R$ 8,692.90	R$ 3,071.01
⋮	⋮	⋮	⋮
10	R$ 14,000.00	R$ 5,397.61	R$ 36,023.94

$$DP = (5-1) + \frac{|-5{,}621.88|}{|-5{,}621.88| + 3{,}071.01} = 4.65$$

Net Present Value (NPV)

NPV is used to calculate, in terms of present value, the value of a project, asset or company. It is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Newman et al., 2020).

The higher the NPV, the more profitable the investment. An investment with NPV > 0 has revenues greater than expenses. If NPV < 0, expenses are greater than revenues. When $NPV = 0$, revenues and expenses are equal and the decision to invest in the project becomes neutral. NPV considers the time value of money and the CFs after payback. However, it is defined in terms of absolute value (monetary units), that is, it does not consider the scale of the project, in terms of size and duration. NPV consists of the sum of investment's DCFs, Equation (4).

$$NVP = \sum_{n=0}^{N} DCF_n \tag{4}$$

For the data in Table 2, NPV is equal to R$ 36,023.94. This value corresponds to the sum of the values from the DCF column (third column), which is equal to the value of the accumulated DCF in the last period (tenth row and fourth column).

Internal Rate of Return (IRR)

IRR is used to evaluate the percentage of profitability from a project. It represents the discount rate, r, which resets the NPV of the cash flows of an investment, in other words, it makes the present value of the inflows equal to the present value of the outflows. Therefore, IRR presents the reversal point of the investment decision, since it is expected, at least, that the return of a project is equal to its cost. IRR is the average intrinsic rate of return that the investor obtains, in each period, for the values of a CF considering NPV = 0 (Newman et al., 2020), as Equation (5).

$$\frac{CF_0}{(1+IRR)^0}+\frac{CF_1}{(1+IRR)^1}+\frac{CF_2}{(1+IRR)^2}+\cdots+\frac{CF_N}{(1+IRR)^N}=0 \tag{5}$$

The higher the IRR, the more profitable the investment. Considering the minimum attractive rate of return ($MARR$), an investment with $IRR > MARR$ is considered attractive. If $IRR = MARR$ the investment is neutral. When $IRR < MARR$ the return on investment is lower than what the company's partners or shareholders require for the application of equity.

IRR considers the time value of money, the CFs after payback and is defined in terms of relative value (expressed as a percentage), that is, it considers the scale of the project. As a disadvantage, IRR assumes that all flows (revenue and expenses) are discounted at the same rate.

There is no algebraic formula to calculate IRR directly. Its calculation involves solving polynomial equations. An alternative is to apply the interpolation method, Equation (6), for two discount rates, final and initial (rf and ri), whose interval contains the IRR, considering the respective NPVs.

$$IRR=\left[r_i+\left(r_f-r_i\right)\cdot\left(\frac{NPV_i}{NPV_i-NPV_f}\right)\right]\cdot 100 \tag{6}$$

For example, Figure 2 shows the graph NPV versus r for the data in Table 3, varying the discount rate from 0 to 100%. As discount rate increases, NPV decreases. IRR is between 20% and 30%, since when NPV crosses the x axis its value is equal to 0.

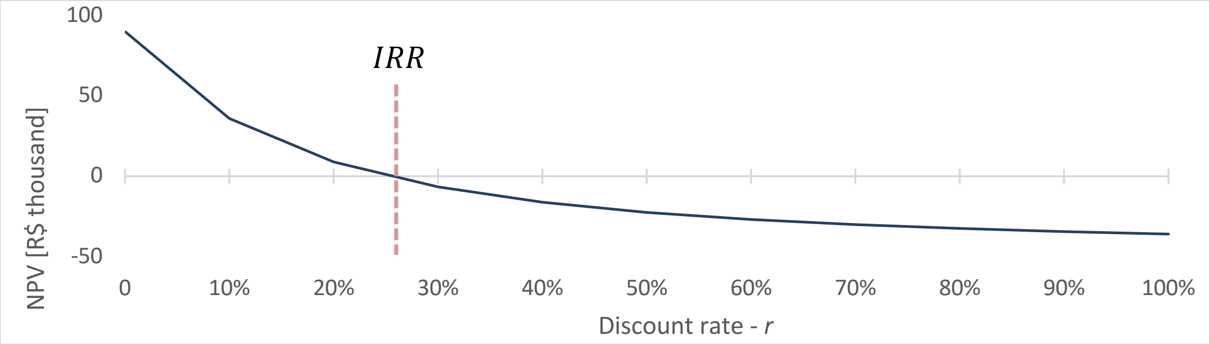


Figure 2 - Graph NPV versus r for the data in Table 3

Table 3 extends Table 2, displaying the NPV (accumulated DCF) for the 20% and 30% discount rates, interval that contains the IRR (in blue on the table). IRR value for the example is 25.64% (calculated in the sequence).

Table 3 - NPV for the 20% and 30%discount rates

Year	CF	DCF (20%)	NPV	DCF (30%)	NPV
0	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00	-R$ 50,000.00
1	R$ 14,000.00	R$ 11,666.67	-R$ 38,333.33	R$ 10,769.23	-R$ 39,230.77
2	R$ 14,000.00	R$ 9,722.22	-R$ 28,611.11	R$ 8,284.02	-R$ 30,946.75
3	R$ 14,000.00	R$ 8,101.85	-R$ 20,509.26	R$ 6,372.33	-R$ 24,574.42
4	R$ 14,000.00	R$ 6,751.54	-R$ 13,757.72	R$ 4,901.79	-R$ 19,672.63
5	R$ 14,000.00	R$ 5,626.29	-R$ 8,131.43	R$ 3,770.61	-R$ 15,902.02
⋮	⋮	⋮	⋮	⋮	⋮
10	R$ 14,000.00	R$ 2,261.08	R$ 8,694.61	R$ 1,015.53	-R$ 6,718.45

$$IRR = \left[0.2 + (0.3 - 0.2) \cdot \left(\frac{8{,}694.61}{8{,}694.61 - (-6{,}718.45)}\right)\right] \cdot 100 = 25.64\%$$

Levelized Cost of Electricity ($LCOE$)

$LCOE$ can be used as a metric to compare different proposals of solar PV systems. It represents the cost to generate a unit of electrical energy from a given system, while the energy tariff represents the cost of purchasing a unit of electrical energy from a specific company (Gomes et al., 2018).

$LCOE$ corresponds to the ratio between the NPV of the costs of a generation asset (I_0 + $O\&M$ costs) and the energy generated by the system during its lifetime. In Equation (7), C_n corresponds to the system costs in the period n and E_n refers to the energy generated by the system also in the period n.

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=0}^{N} E_n} \tag{7}$$

For example, suppose that the $LCOE$ of an asset is estimated at 0.56 R$/kWh while the company charges 0.70 R$/kWh for the energy tariff. In this case, the investor can generate their own energy for a value of at least 20% lower than that offered by the distributor.

As a limitation of the $LCOE$, it should be noted that the cost considered is not equivalent to value. The lower cost shown may be associated with a lower quality system or service. Therefore, like the other viability indicators, $LCOE$ should not be used as the only metric.

3.2 Mathamatical model

The proposed mathematical model consists of the development of a DCF for the investment. For solar PV systems, the DCF assumes as input the net revenue (saved cost) due to the energy generated by the system, $Ger_n.(1-\alpha).Tar_n.(1+\beta)$. For the first factor of this product, the calculation involves the energy generated, consumed, injected into the grid, and compensated by the system. The net revenue contemplates the energy consumed and compensated, that is, the benefits brought by the system. The output corresponds to expenses with maintenance, system insurance, and inverter replacement, $O\&M_n.(1+\gamma)$.

The DCF considers the time value of money. Therefore, the estimated CFs are discounted at a rate, r. The objective is to bring the nominal values of each period to the present, Equation (8). Details about data, scenarios, parameters, and other assumptions are described in the next section.

$$DCF_n = \frac{Ger_n\,.(1-\alpha)\,.Tar_n\,.(1+\beta) - O\&M_n\,.(1+\gamma)}{(1+r)^n} \tag{8}$$

where:

n period or year of the DCF;

Ger_n average PV generation in the year n, considering surplus compensation [kWh];

α degradation rate of the PV system [%];

Tar_n average energy tariff in the year n [R$/kWh];

β readjustment rate of the energy tariff [%];

$O\&M_n$ cost of maintenance and insurance of the system in the year n [R$];

γ readjustment rate of the $O\&M$ costs [%];

r annual discount rate applied to CFs [%].

From Equation (8), it is possible to calculate DP, NPV, IRR, and $LCOE$ viability indicators in equations (3), (4), (6), and (7); respectively. DP and IRR can be calculated as Tables 2 and 3, considering the DCF defined in Equation (8) for solar PV investments. Since $DCF_0 = I_0$, NPV in Equation (4) can be rewritten as Equation (9).

$$NPV = -I_O + \sum_{n=1}^{N} \frac{Ger_n\,.\,(1-\alpha)\,.\,Tar_n\,.\,(1+\beta) - O\&M_n\,.\,(1+\gamma)}{(1+r)^n} \tag{9}$$

From Equations (8) and (9), $LCOE$ viability indicator in Equation (7) can be rewritten as Equation (10). In this equation, C_n includes the costs of initial investment and operation/maintenance of the system; En corresponds to the average solar PV generation in the year n for the EECS.

$$LCOE = \frac{I_0 + \sum_{n=1}^{N} \frac{O\&M_n}{(1+r)^n}}{\sum_{n=0}^{N} Ger_n} \tag{10}$$

4. Data

The case studies are carried out according to the data described in Sections 4.1 to 4.4. These sections present the data related to (4.1) consumer units, (4.2) PV systems, (4.3) Scenarios, and (4.4) model parameters.

4.1. Consumer units

Three consumer units located in the state of Sao Paulo were chosen as study object. Their consumption levels are classified in this study as low, middle, and high. These consumer units have an energy supply contract with Companhia Piratininga de Força e Luz (CPFL). They belong to Group B1 of consumers, served at residential voltage (less than or equal to 25 kW).

Table 4 presents the extreme and average values for the year of highest consumption of each unit, considering the last five years. It contains the minimum, maximum, and average values of consumption [kWh]. These data, provided by the distribution company, are important for sizing the PV systems.

Table 4 - Minimum, maximum, and average energy consumption of the three units

Consumption [kWh]	Low	Middle	High
Minimum	170	349	765
Maximum	318	684	1,187
Average	235	463	1,003

4.2. PV systems

For each consumer unit a PV system configuration was defined in 2023 by specialized company in services, equipment, labor, and installation materials of PV systems; using a commercial software. The proposals consider an on-grid PV system, panels installed facing the north and inclination of 20º to prevent dust from accumulating.

The technical specifications and acquisition cost of the PV systems for each consumer unit are presented in Table 5. Considering the data provided (average monthly generation and area) and an average insolation of 5,000 Wh/m^2 it is possible to estimate the efficiency of the systems at approximately 16%, as Villalva (2016).

Table 5 - PV project data for the three consumer units

Technical and cost data	Low	Middle	High
Nominal power [kWp]	2.20	4.40	8.80
Number of modules	4	8	16
Estimated area [m^2]	11	22	44
Estimated average monthly generation [kWh]	264.00	528.00	1,104.00
Total cost of the system [R$]	10,290.52	17,424.07	28,023.18
Cost / Power [R$/Wp]	4.68	3.96	3.18

4.3 Scenarios

Sensitivity analysis relates to uncertainties in the input variables or parameters of a model used for decision making. In order to check the sensitivity of a model, variables or parameters that significantly influence the results are chosen so that the effect of their changes on the results is observed (Park, 2019).

The economic viability of PV investments is examined for the three EECSs presented in Section 2: previous (EECS = 100%), current (EECS = 72%), and considered (EECS = 38%). For each of them, three consumer units (Low, Middle, and High) and four discount rates (5%, 10%, 15%, and 20%) are considered.

For the four chosen discount rates, three main economic indices in Brazil were used. These indices were employed due to their importance for the national economy. They are known as IPCA, IGP-M, and SELIC.

- The Extended National Consumer Price Index (acronym in Portuguese: IPCA) measures the price variation of a range of goods and services consumed by the population, considering the weight they have on family budget (IBGE, 2024).

- The General Price Index - Market (acronym in Portuguese: IGP-M) measures the variation in prices of goods, services, and raw materials used in agricultural, industrial, and civil construction production (FGV, 2024).
- The Special Settlement and Custody System (acronym in Portuguese: SELIC) refers to the interest rate determined in one-day loan operations among financial institutions that use public bonds of the National Treasury as collateral. It is the economy's basic interest rate (BCB, 2024).

Figure 3 shows historical data (2010-2023) and projection (2024-2026) of the IPCA, IGP-M, and SELIC in Brazil; extracted from IBGE (2024), FGV (2024), and BCB (2024). The average of the data in this figure for the three indices is 7.31%. Considering the highest value of each index (IPCA: 10.67%, IGP-M: 23.14%, and SELIC: 14.15%) the average is 15.99%. Therefore, for the discount rates, multiples of 5 were adopted, which include the mentioned averages of 7.31% and 15.99%; justifying the selected values of 5%, 10%, 15%, and 20%.

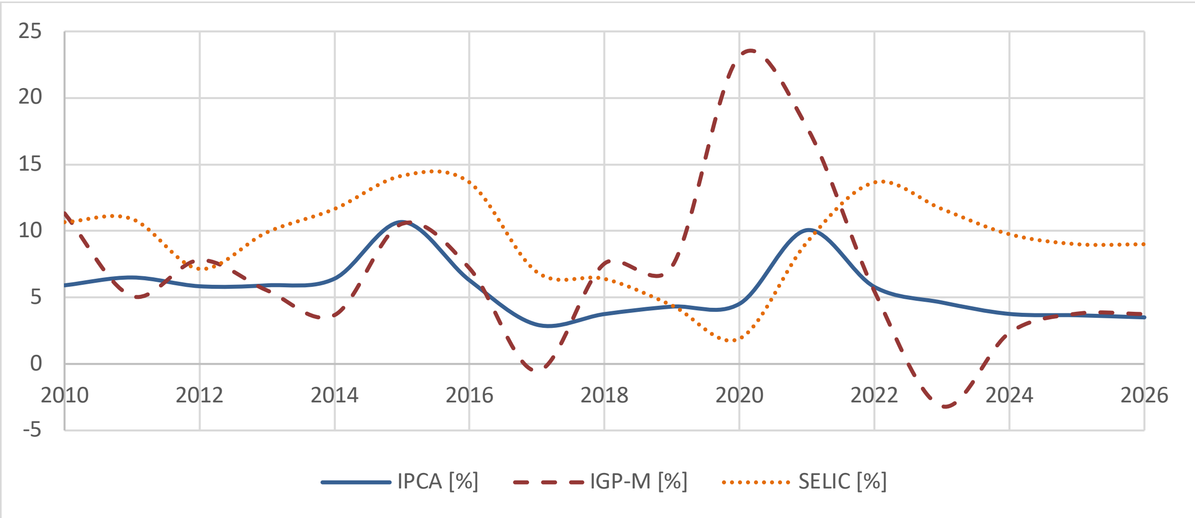


Figure 3 - Historical data (2010-2023) and projection (2024-2026) of the IPCA, IGP-M, and SELIC

In total, the combination of three EECSs, three consumer units, and four discount rates, results in 36 analyzed scenarios, presented in Table 6.

Table 6 - Scenarios for studying economic viability of PV systems ($3 \cdot 3 \cdot 4$ combinations $= 36$ scenarios)

Net-metering	Consumption	Discount Rate (r)
Previous (EECS = 100%)	Low, Middle, High	5%, 10%, 15%, 20%
Current (EECS = 72%)	Low, Middle, High	5%, 10%, 15%, 20%
Considered (EECS = 38%)	Low, Middle, High	5%, 10%, 15%, 20%

4.4 Model parameters

As can be seen in Equations (8)-(10), studies of economic viability depend on several parameters. These include period considered for the analysis [years], degradation rate of the PV system [%], adjustment rate of the energy tariff [%], $O\&M$ costs related to the initial investment [%], and readjustment rate of the $O\&M$ costs [%].

In regards to the period considered for the analysis, NREL (2016) estimates the useful life of PV systems to be approximately 25 to 40 years depending on various factors, such as environmental conditions. As far as the productive life of a solar panel, modules are typically warrantied for 20–25 years, after which they can still produce electricity, but the level of actual output is no longer guaranteed. Thus, the period considered for the analysis, [N], is 25 years.

In relation to the degradation rate of PV systems, NREL (2018) has shown that solar panels present an average performance reduction rate of around 0.5% per year, which can be higher in hot climates. Rocha et al. (2017), Vale et al. (2017), Fontoura et al. (2018), and Giovanini et al. (2020) adopt a value between 0.7% and 0.8% for annual loss of module efficiency. Considering these researches, 0.7% is used as the degradation rate of the PV systems, [α].

For the adjustment rate of the energy tariff, it is possible to consult the values from 2018 to 2022 for CPFL Piratininga consumers at CPFL (2023). Considering the readjustments of the last five years (18.70%, -11.28%, 8.95%,16.40%, and 9.60%) for Group B participants, the average annual rate [β] adopted is 8.47%.

The operation and maintenance costs with PV systems are estimated not to exceed 1% per year of the total invested value. As in Holdermann et al. (2013) and Rocha et al. (2017), in this research 0.5% of the initial investment is used as value for $O\&M$ costs. In relation to the readjustment rate of the $O\&M$ costs, [γ], the value of 0.1% is adopted.

The fixed parameters for the 36 scenarios evaluated are listed in Table 7. Based on the recent effective cost of the energy tariff from the consumer units, the value of 0.88 R$/kWh was adopted as the initial energy tariff.

Table 7 - Parameters for calculating $DCFs$

Description	Variable	Value
Number of years considered for the analysis	N	25 years
Degradation rate of the PV systems	α	0.7%
Adjustment rate of the energy tariff	β	8.47%
Annual cost of system maintenance in relation to I_0	$O\&M$	0.5%
Adjustment rate of the $O\&M$ costs	γ	0.1%

5.Results and Discussion

The results and discussion are organized in four sub-sections. Sub-section 5.1 presents IRR, $LCOE$, DP, and NPV of the consumer unit projects (Low, Middle, and High) for the three EECSs (100%, 72%, and 38%). In this sub-section, the relationship between PV projects and viability indicators is assessed. In Sub-section 5.2, the effect of the four discount rates adopted (5%, 10%, 15%, and 20%) on DP and NPV is analyzed, considering extreme scenarios. In Sub-section 5.3 the impact of the net-metering policies on the viability of PV investments is examined, showing the variation in IRR, $LCOE$, DP, and NPV from the evaluated scenarios. Lastly, Sub-section 5.4

shows how the results differ across different energy consumption levels, discount rates, and compensation systems for the most current and probable variables.

5.1. Consumer unit projects (Low, Middle, and High)

Tables 8-10 present the results from the 36 chosen scenarios, showing the viability indicators of the consumer unit projects (Low, Middle, and High) for previous, current, and considered EECSs (100%, 72%, and 38%). For IRR and $LCOE$ average values are presented, while for DP and NPV the four discount rates adopted in this research (5%, 10%, 15%, and 20%) are considered.

Table 8 - Results for previous alternative (EECS = 100%)

Consumption		Low	Middle	High
IRR [%]		34	39	49
$LCOE$ [R$/kWh]		0.15	0.12	0.10
r = 5%	DP [years]	3.80	3.23	2.50
	NPV [R$]	80,634.19	164,649.94	353,275.27
r = 10%	DP [years]	4.27	3.58	2.72
	NPV [R$]	39,034.73	81,370.79	178.932,38
r = 15%	DP [years]	4.88	4.01	2.98
	NPV [R$]	20,180.01	43,619.62	99,887.00
r = 20%	DP [years]	5.73	4.58	3.30
	NPV [R$]	10,615.89	24,467.21	59,776.68

Table 9 - Results for current alternative (EECS = 72%)

Consumption		Low	Middle	High
IRR [%]		32	37	46
$LCOE$ [R$/kWh]		0.16	0.13	0.10
r = 5%	DP [years]	4.08	3.47	2.69
	NPV [R$]	74,218.21	151,817.98	326,444.82
r = 10%	DP [years]	4.62	3.87	2.94
	NPV [R$]	35,549.03	74,399.38	164,355.80
r = 15%	DP [years]	5.33	4.37	3.24
	NPV [R$]	18,023.65	39,306.90	90,869.51
r = 20%	DP [years]	6.36	5.03	3.60
	NPV [R$]	9,134.54	21,504.51	53,581.93

Table 10 - Results for considered alternative (EECS = 38%)

Consumption		Low	Middle	High
IRR [%]		30	34	42
$LCOE$ [R$/kWh]		0.17	0.15	0.11
r = 5%	DP [years]	4.47	3.81	2.95
	NPV [R$]	66,427.38	136,236.32	293,864.98
r = 10%	DP [years]	5.11	4.28	3.25
	NPV [R$]	31,316.39	65,934.09	146,655.66

r = 15%	DP [years]	5.99	4.89	3.61
	NPV [R$]	15,405.22	34,070.04	79,919.70
r = 20%	DP [years]	7.34	5.75	4.05
	NPV [R$]	7,335.75	17,906,94	46,059,74

The results show that project High is the most profitable, followed by project Middle, and then by project Low. The interpretation of the results is associated with the technical and cost data of the projects presented in Table 5. This table shows that the cost/power ratio [R$/Wp] is lowest for project High, followed by project Middle, with project Low being the one with the highest cost per Wp. Therefore, as expected, in Tables 8-10 IRR decreases in the order High-Middle-Low; while $LCOE$ and DP increase in the same order.

Table 5 also shows that the total cost of the system [R$] is lower for project Low, followed by project Middle, with project High being the one with the highest total installation cost. As explained in Section 3, NPV is defined in terms of absolute value, that is, this indicator is biased towards presenting a higher NPV for projects with large initial investment, even if they are not better in relative terms. Thus, in Tables 8-10, NPV increases in the order Low-Middle-High.

Considering the most optimistic and pessimistic scenarios from the investor's point of view (EECS = 100% with r = 5% and EECS = 38% with r = 20%), Tables 8-10 shows that:

- For project Low, IRR varies from 34% to 30%, $LCOE$ ranges from 0.15 R$/kWh to 0.17 R$/kWh, DP increases from 3.80 years to 7.34 years, and NPV decreases from R$ 80,634.19 to R$ 7,335.75.
- For project Middle, IRR varies from 39% to 34%, $LCOE$ ranges from 0.12 R$/kWh to 0.15 R$/kWh, DP increases from 3.23 years to 5.75, and NPV decreases from R$ 164,649.94 to R$ 17,906.94.
- For project High, IRR varies from 49% to 42%, $LCOE$ ranges from 0.10 R$/kWh to 0.11 R$/kWh, DP changes from 2.50 years to 4.05, and NPV decreases from R$ 353,275.27 to R$ 46,059.74.

It is worth highlighting that IRR value for the project High in the most pessimistic scenario (Table 10), 42%, is higher than the IRR for the project Low even in the most optimistic scenario, 34% (Table 8). It also happens for the other viability indicators ($LCOE$, DP, and NPV), as long as the same discount rate is adopted. This shows how important the project characteristics are in the viability analysis.

Table 11 presents the percentage variation of the viability indicators previously listed. For each viability indicator, the direction of the vertical arrows specifies whether the change corresponds to an increase or decrease in the variable. As can be seen, the percentage variation of the IRR increases in the order Low-Middle-High, while for DP and NPV it decreases in the same order. There is no significant change for $LCOE$ indicator.

Table 11 – Percentage variation of the viability indicators from the most optimistic to the most pessimistic scenarios from the investor's point of view

Indicator	Low [%]	Middle [%]	High [%]	Mean [%]
IRR $\downarrow$	12.48	12.75	13.21	12.81
$LCOE$ $\uparrow$	18.34	18.34	18.34	18.34
DP $\uparrow$	93.06	77.74	61.90	77.57
NPV $\downarrow$	90.90	89.12	86.96	89.00

According to Table 11, the percentage variation of IRR, $LCOE$, DP, and NPV for extreme scenarios presents high mean values, being the smallest equal to 12.81% and the largest equal to 89.00%. Therefore, project characteristics, discount rates, and EECSs significantly affect the analysis of PV investments.

<u>5.2. Discount rates (5%, 10%, 15%, and 20%)</u>

Figures 4 and 5 illustrate the DP variation, considering r = 5%, 10%, 15%, and 20% by consumer unit project, for EECS = 100% (Normative Resolution nº 482/2012) and EECS = 38% (Regulatory Impact Analysis nº 03/2019); respectively. The objective is to evaluate the impact of the discount rates on the DP for extreme scenarios (Tables 8 and 10).

From the data in Figures 4 and 5, Table 12 presents the percentage increase in DP value of each project, considering the variations in discount rate. It is noted that for the system with greater compensation (EECS = 100%) the percentage increases in DP are smaller than for the system with limited compensation (EECS = 38%). That means, the lower the energy compensation, the greater the impact of the discount rate on the viability analysis. On average, changing the discount rate from 5% to 10%, 15%, and 20% impacts the DP value by 11.55%, 26.11%, and 46.09%; respectively.

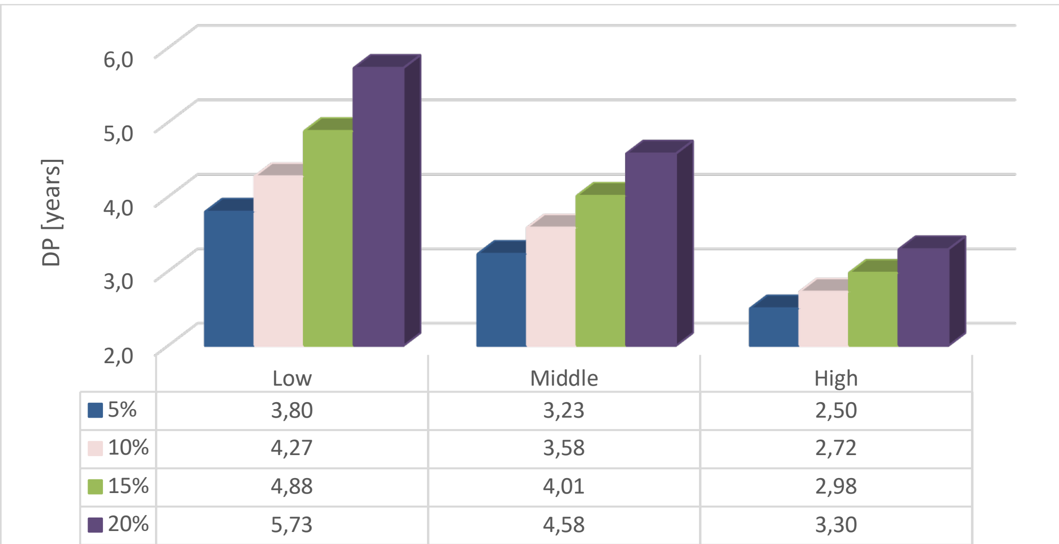


Figure 4 - DP for the four rates by consumer unit project (EECS = 100%)

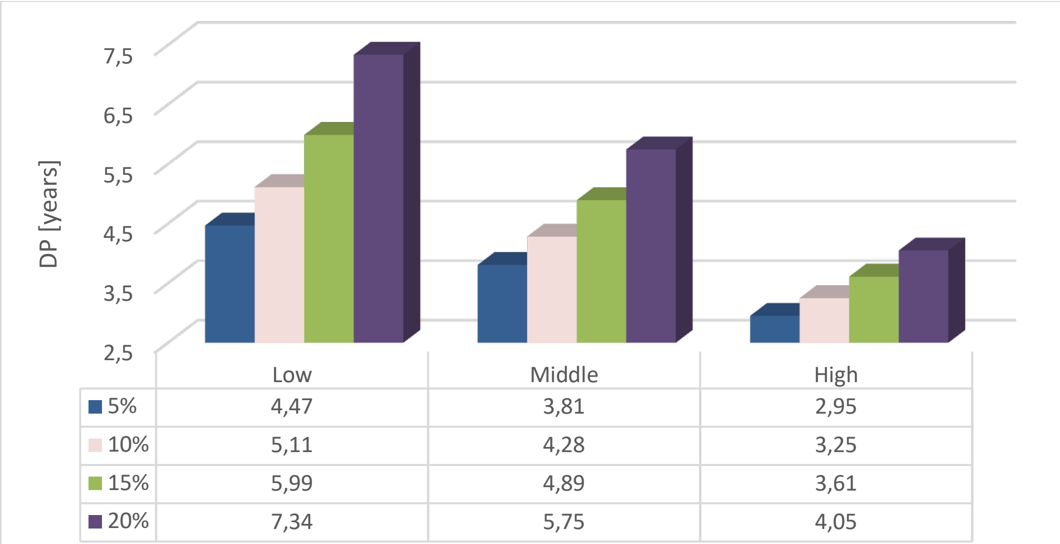


Figure 5 - DP for the four rates by consumer unit project (EECS = 38%)

Table 12 - Percentage increase in DP value for variations in the discount rate from 5% to 10%, 15%, and 20%

r [%]	EECS = 100%			EECS = 38%			Mean
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]	[%]
$5 \rightarrow 10$	12.47	10.90	8.96	14.42	12.49	10.05	11.55
$5 \rightarrow 15$	28.51	24.13	19.13	34.04	28.55	22.29	26.11
$5 \rightarrow 20$	50.82	41.69	31.77	64.16	50.93	37.19	46.09

Figures 6 and 7 illustrate the NPV variation, considering r = 5%, 10%, 15%, and 20% by consumer unit project, for EECS = 100% (Normative Resolution nº 482/2012) and EECS = 38% (Regulatory Impact Analysis nº 03/2019); respectively. Similar to what was done previously, the objective is to evaluate the impact of the discount rates on the NPV for extreme scenarios (Tables 8 and 10).

From the data in Figures 6 and 7, Table 13 presents the percentage decrease in NPV value of each project, considering the variations in discount rate. Again, it is possible to realize that for the system with greater compensation (EECS = 100%) the percentage reductions in NPV are smaller than for the system with limited compensation (EECS = 38%). On average, changing the discount rate from 5% to 10%, 15%, and 20% impacts the NPV value by 51.01%, 74.14%, and 85.87%; respectively. As can be observed, the definition of the net-metering policies even affects the sensitivity of the investment in relation to country discount rate.

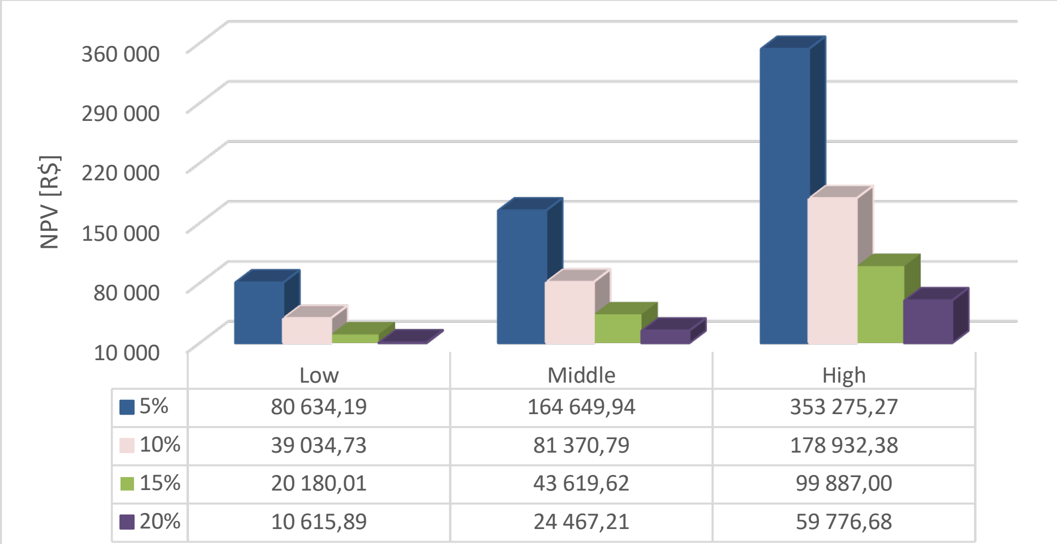


Figure 6 - *NPV* for the four rates by consumer unit project (EECS = 100%)

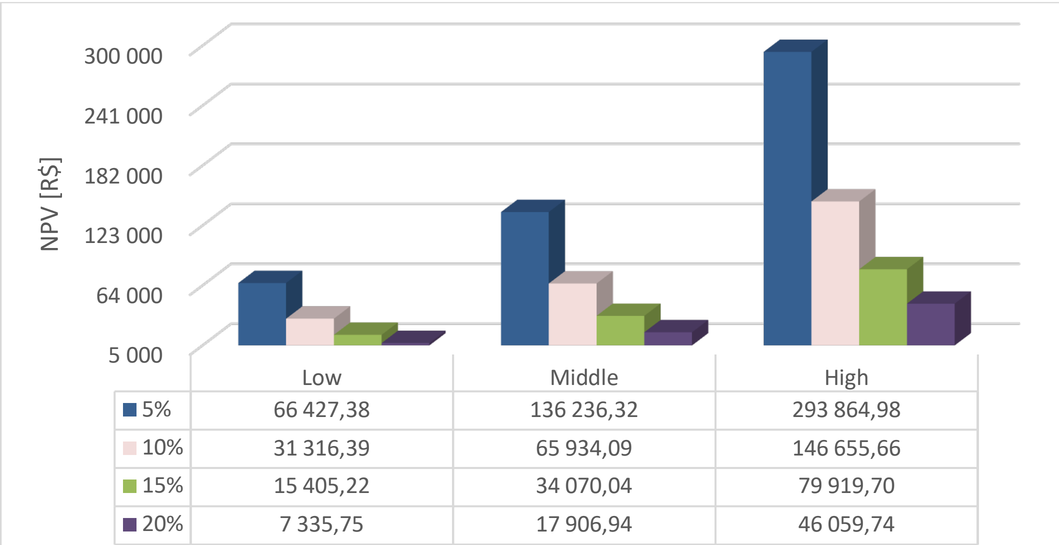


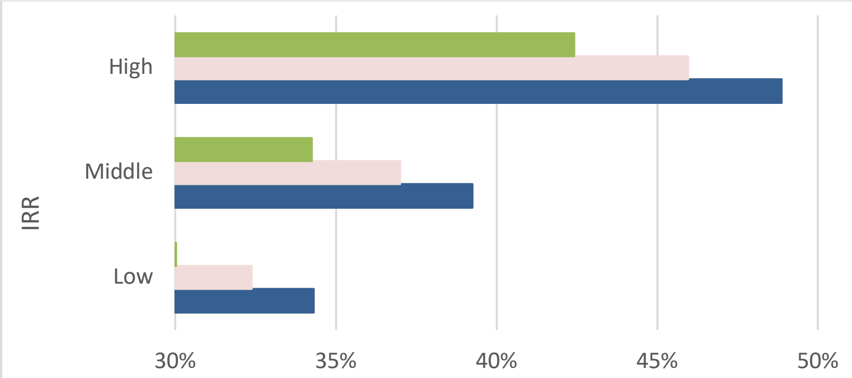
Figure 7 - *NPV* for the four rates by consumer unit project (EECS = 38%)

Table 13 - Percentage decrease in NPV value for variations in the discount rate from 5% to 10%, 15%, and 20%

r [%]	EECS = 100%			EECS = 38%			Mean [%]
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]	
5→10	51.59	50.58	49.35	52.86	51.60	50.09	51.01
5→15	74.97	73.51	71.73	76.81	74.99	72.80	74.14
5→20	86.83	85.14	83.08	88.96	86.86	84.33	85.87

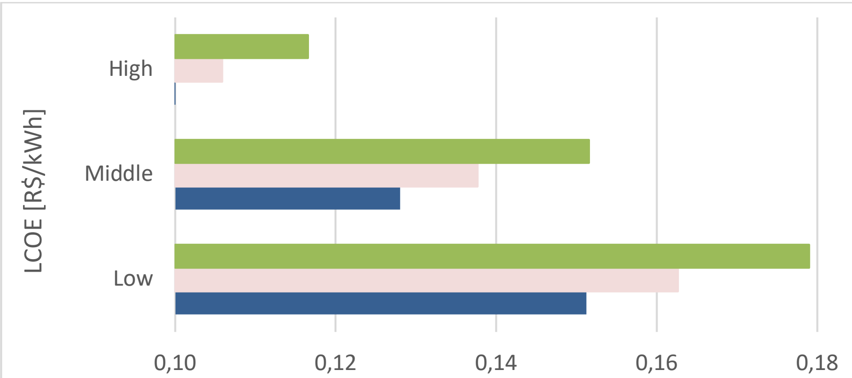
<u>5.3 Net-metering policies (EECS = 100%, 72%, and 38%)</u>

Figure 8-11 illustrate the impact of the net-metering policies presented by Normative Resolution nº 482/2012, Regulatory Impact Analysis nº 03/2019, and Law nº 14.300/2022 on the IRR, $LCOE$, DP, and NPV of the consumer unit projects (Low, Middle, and High). Comparisons are presented for r = 10%, considering the SELIC at the end of 2023 (11.65%) and the average of IPCA, IGP-M, and SELIC (7.31%), as Figure 2.



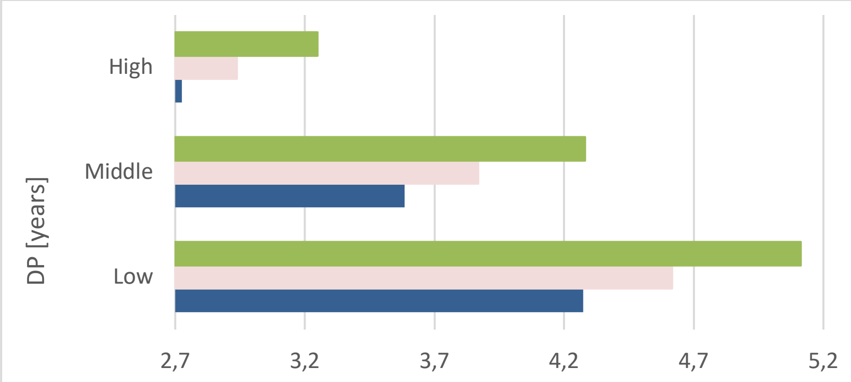
	Low	Middle	High
EECS = 38%	30,02%	34,25%	42,42%
EECS = 72%	32,38%	37,00%	45,96%
EECS = 100%	34,30%	39,26%	48,88%

Figure 8 - IRR for net-metering policies by consumer unit project



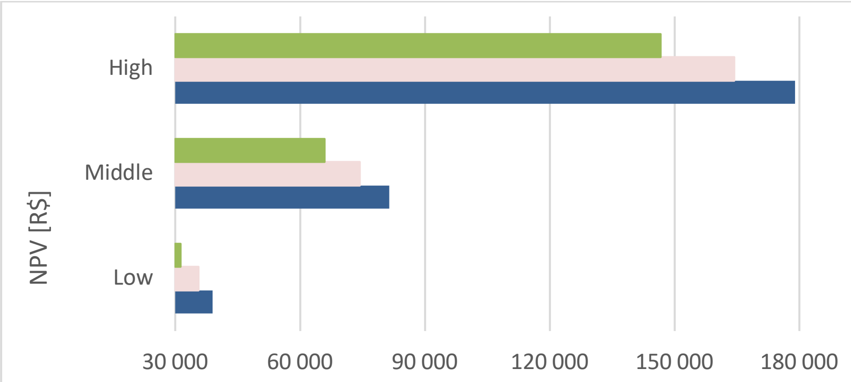
	Low	Middle	High
EECS = 38%	0,18	0,15	0,12
EECS = 72%	0,16	0,14	0,11
EECS = 100%	0,15	0,13	0,10

Figure 9 - $LCOE$ for net-metering policies by consumer unit project



	Low	Middle	High
EECS = 38%	5,11	4,28	3,25
EECS = 72%	4,62	3,87	2,94
EECS = 100%	4,27	3,58	2,72

Figure 10 - DP for net-metering policies by consumer unit project



	Low	Middle	High
EECS = 38%	31 316,39	65 934,09	146 655,66
EECS = 72%	35 549,03	74 399,38	164 355,80
EECS = 100%	39 034,73	81 370,79	178 932,38

Figure 11 - NPV for net-metering policies by consumer unit project

From the data in Figures 8-11, Table 14 presents the percentage variation in IRR, $LCOE$, DP, and NPV of the consumer unit projects, considering EECS = 72% and EECS = 38% and adopting EECS = 100% as a reference. Table 15 shows the average values grouped by EECS. Again, for each viability indicator, the direction of the vertical arrows specifies whether the change corresponds to an increase or decrease in the variable.

Table 14 - Impact of the net-metering policies for the viability indicators by consumer unit project – individual values

Indicator [%]	EECS 100% → 72%			EECS 100% → 38%		
	Low [%]	Middle [%]	High [%]	Low [%]	Middle [%]	High [%]
IRR ↓	5.61	5.74	5.96	12.48	12.75	13.21
$LCOE$ ↑	7.53	7.53	7.53	18.34	18.34	18.34
DP ↑	8.03	7.91	7.79	19.65	19.45	19.19
NPV ↓	8.93	8.57	8.15	19.77	18.97	18.04

Table 15 - Impact of the net-metering policies for the viability indicators grouped by EECS – average values

Indicator [%]	EECS 100% → 72%	EECS 100% → 38%
IRR ↓	5.77	12.81
$LCOE$ ↑	7.53	18.34
DP ↑	7.91	19.43
NPV ↓	8.55	18.93

According to Tables 14 and 15, in relation to the previous EECS (100%) the current EECS (72%) affects the investments, as follows:

- For project Low, IRR and NPV decrease 5.61% and 8.93%, respectively; while $LCOE$ and DP increase 7.53% and 8.03%, respectively.
- For project Middle, IRR and NPV decrease 5.74% and 8.57%, respectively; while $LCOE$ and DP increase 7.53% and 7.91%, respectively.
- For project High, IRR and NPV decrease 5.96% and 8.15%, respectively; while $LCOE$ and DP increase 7.53% and 7.79%, respectively.

Still according to Tables 14 and 15, in relation to the previous EECS (100%) the considered EECS (38%) would affect the investments, as follows:

- For project Low, IRR and NPV would decrease 12.48% and 19.77%, respectively; while $LCOE$ and NPV would increase 18.34% and 19.65%, respectively.
- For project Middle, IRR and NPV would decrease 12.75% and 18.97%, respectively; while $LCOE$ and NPV would increase 18.34% and 19.45%, respectively.
- For project High, IRR and NPV would decrease 13.21% and 18.04%, respectively; while $LCOE$ and NPV would increase 18.34% and 19.19%, respectively.

5.4 Viability indicators across different projects, rates, and compensations

Finally, Table 16 presents the percentage variation of the viability indicators across different energy consumption levels (Low, Middle, and High), discount rates (5%, 10%, 15%, and 20%), and compensation systems (EECS = 100%, 72%, and 38%). In this analysis, in each scenario, the value of the variables which are not being evaluated is defined as the most current or probable (for example, Project = Middle, r = 10%, and EECS = 72%). The objective is to evaluate scenarios with a high probability of occurrence and neutralize, as much as possible, the influence of these variables in the analysis.

Table 16 – Percentage variation of the viability indicators across different (a) energy consumption levels, (b) discount rates, and (c) compensation systems

Scenario		IRR [%]	$LCOE$ [%]	DP [%]	NPV [%]
(a)	Level (Low→Middle)	↑ 15.63	↓ 18.75	↓ 16.23	↑ 109.29
	Level (Middle→High)	↑ 24.32	↓ 23.08	↓ 24.03	↑ 120.91
	Difference	*1.6 times*	*1.2 times*	*1.5 times*	*1.1 times*
(b)	r (5% → 10%)	-	-	↑ 11.53	↓ 50.99
	r (10% → 15%)	-	-	↑ 12.92	↓ 47.17
	r (15% → 20%)	-	-	↑ 15.10	↓ 45.29
	Difference on average			*1.1 times*	*1.1 times*
(c)	EECS (100% → 72%)	↓ 5.13	↑ 8.33	↑ 8.10	↓ 8.57
	EECS (72% → 38%)	↓ 8.11	↑ 15.38	↑ 10.59	↓ 11.38
	Difference	*1.6 times*	*1.8 times*	*1.3 times*	*1.3 times*

As justified in Section 5.1, investment profitability increases from Low to High consumption level. Therefore, for analysis across different energy consumption levels, item (a) of Table 16, IRR and NPV increase and $LCOE$ and DP decrease from Low to High. It is possible to realize that the percentage variation of all viability indicators is lower for Low→Middle than for Middle→High energy consumption level. From Low→Middle to Middle→High the percentage change in indicators is at least 1.1 times, reaching up to 1.6 times.

For analysis across different discount rates, item (b) of Table 16, the percentage variation of indicators is evaluated for each 5% increase in the discount rate. As justified in Section 5.2, where the r = 5% is adopted as a reference, DP increases and NPV decreases as the discount rate rises. The results show that every 5% increase in the discount rate, the percentage change in indicators is, on average, 1.1 times; ranging from 1.0 to 1.2.

Regarding the analysis across different compensation systems, item (c) of Table 16, the percentage variation of indicators for previous, current, and considered EECS is analyzed. As justified in Section 5.3, where the EECS = 100% is adopted as a reference, IRR and NPV decrease and $LCOE$ and DP increase from 100% to 38% compensation system. According to the data, from 100%→72% to 72%→38% the percentage change in indicators is at least 1.3 times, reaching up to 1.8 times.

In summary, the data on Table 16 indicates that the viability of solar PV investments is significantly impacted by the energy consumption level, discount rate adopted, and compensation system in force. Furthermore, when comparing results across projects (Low→Middle→High), r (5→10→15→20%), and EECS (100→72→38%), especially the last line of each item on Table 16 (referred as "Difference"), it is noted that for the data considered in this research, the viability indicators are highly influenced by the compensation system, energy consumption level, and discount rate adopted; in this order. That is justified by the highest difference found for the respective items on Table 16 “c” (1.8 times), “a” (1.6 times), and “b” (1.1 times).

6. Key Findings, Comparison with Previous Studies, and Economic/Policy/Social Implications

Energy transition is a process of worldwide importance that aims to reduce global warming. Among the different ways of contributing to this process, Distributed Generation (DG) using solar Photovoltaic (PV) stands out, especially in Brazil. In order to encourage the growth of this energy source, regulatory mechanisms are adopted, such as net-metering for energy compensation.

Changes in the compensation mechanisms affect the economic viability of solar PV investments and the attractiveness for participants. Therefore, Brazilian Electricity Regulatory Agency (ANEEL) has worked to create a model that keeps the solar sector growing and minimizes the impacts for energy tariff, distribution companies, consumers, prosumers, etc.

Regarding the findings of this research, Section 5.1 showed that technical and cost data of the projects significantly impact the viability of investment. For example, the return for High consumption level in the most pessimistic scenario (Table 10 - 42%) is higher than for the Low consumption level even in the most optimistic scenario (Table 8 - 34%). That is justified by the lower cost/power [R$/Wp] of the High consumption level in relation to Low and Middle consumption levels.

Section 5.2 revealed that the compensation mechanism also affects the sensitivity of the investment in relation to discount rate. The lower the energy compensation, the greater the impact of the discount rate on the viability indicators. For example, the percentage variations in DP (Table 12) and NPV (Table 13) are smaller for EECS = 100% than for EECS = 38%. That is justified by the weight of the energy compensation in the mathematical model developed, Equation (8).

From Section 5.3, it was possible to observe that from the previous (EECS = 100%) to current (EECS = 72%) compensation mechanism the return for investor, on average, decreased 5.77% (Table 15 - left side). However, this reduction would be of 12.81% if considered (EECS = 38%) compensation mechanism was adopted (Table 15 - right side).

Finally, Section 5.4 showed that among the three analyzes performed (energy consumption levels, discount rates, and compensation systems) the last one has a greater impact on viability indicators. That can be confirmed by the highest difference found for each item of Table 16.

Concerning the economic implications, lower EECS reduces the investment attractiveness. It is worth emphasizing that the high interest rates charged by Brazilian financing institutions also reduces return on investment and the economic feasibility of solar PV systems. However, for the studies carried out, even in the worst case (Project = Low, r = 20%, and EECS = 38%) the investment remains viable, with positive NPV and DP less than 8 years. Therefore, solar PV systems investments are competitive in Brazil.

Positive results for all scenarios were also obtained by Santos & Lucena (2021). In this research, it was concluded that the economic potential is not affected by climate change in all scenarios. Vieira & Carpio (2020) also found positive values. Based on the parameters applied in that study, the conclusion shows that the tariff subsidy for grid-connected PV generation is no longer needed in Brazil.

Drumond Jr. et al. (2021) concludes that there is a large variation in the results among the Brazilian states and distribution companies. Thus, they affirm that DG from solar PV systems still depend on government incentives to continue increasing adoption in Brazil. Iglesias & Vilaça (2022) indicates that appropriated regulation would be between the previous and current EECS. According to that study, the solar PV market growth reduction could directly impact Brazil's commitment to reducing CO_2 emissions, especially in light of the water crisis in which DG can be considered one of the main sources of complementary thermal power plants shares.

In regards to policy/social implications, the previous rule (EECS = 100%) is the most beneficial for investor's point of view, since the compensation is applied to all components of the residential energy tariff. However, in this case, there is a loss of revenue for the distribution companies, forcing them to charge non-PV owners. In this situation, non-PV owners subsidize grid costs for solar PV owners. According to Iglesias & Vilaça (2022), there is a transfer of income from people with adverse financial conditions (non-PV owners) to those in a more favorable financial situation (solar PV owners), which may increase social inequality. As Vieira & Carpio (2020), energy security must be ensured by policies that appropriately allocate costs among consumers.

In this context, the current rule (EECS = 72%) requires the payment of the Distribution Line over the energy consumed, independently of the energy injected into the grid. This alternative mitigates the problems mentioned in the previous paragraph, higher tariffs and social inequality. According to the results of this research, from previous to current rule (EECS = 100→72%) the DP and $LCOE$ increase around 8% and the investment remains viable. Therefore, the existing policy, EECS = 72%, is suitable for the current stage of sector development, minimizing the impacts for energy tariff, distribution companies, consumers, and prosumers.

For EECS = 38%, it is important to take into account the Paris Agreement. Brazil has committed to reduce greenhouse gas emissions, achieving an estimated 45% share of renewable energy in the energy matrix (UN, 2024). Thus, an extremely restricted compensation mechanism, such as EECS = 38%, that decreases the solar PV investment attractiveness and leads to a reduction in number of solar PV adopters could difficult accomplishment of the goals set in Paris Agreement. Furthermore, EECS = 38% can lead loss of jobs created by solar business sector.

Therefore, due to the strong economic, political, and social impact of the changes in the compensation rules, decision makers should follow the expansion of intermittent power sources, especially solar PV, and their impact to the distribution grid by 2029. The objective is to evaluate the consequences of Law nº 14.300/2022 for consumers, companies, and solar business sector. It is important to highlight that the technological evolution of components, batteries, connection of electric vehicles to the grid, and free residential market can lead to further updates to the energy compensation mechanism.

7.Conclusions, Limitations, and Future Works

Although the case studies, results, and policies in this research are specific to Brazilian legislation, the methodology presented can be adapted to any country, even if it employs a different energy compensation mechanism (adaptations might be required depending on tariff regimes). Results and policies depend on the input variables, parameters, assumptions and context of the country; for this reason, they are specific for each case study. Overall, considering all consumer unit projects (Low, Middle, and High), discount rates (5%, 10%, 15%, and 20%), and EECSs (100%, 72%, and 38%); the viability indicators (IRR, $LCOE$, DP, and NPV) showed high percentage variation between extreme scenarios. Therefore, project characteristics, discount rates, and EECSs significantly affect the analysis of PV investments.

Regarding consumer units (High, Middle, and Low), the results showed that project High is the most profitable, followed by project Middle, and then by project Low. That is justified by the technical and cost data of the considered projects. Project High presents the lowest cost/power ratio [R$/Wp]. It is worth mentioning that the viability indicators for the project High in the most pessimistic scenario (EECS = 38%) showed better results than for the project Low even in the most optimistic scenario (EECS = 100%), as long as the same discount rate is adopted. That shows how important the technical and cost characteristics of the projects are in the viability analysis.

In relation to effect of the discount rates (5%, 10%, 15%, and 20%) on viability indicators, it was possible to realize that percentage increase in DP and percentage decrease in NPV from the scenarios 5%→10%, 5%→15%, and 5%→20% is smaller for EECS = 100% than EECS = 38%. That means, the lower the energy compensation, the greater the impact of the discount rate on the viability analysis. Thus, the definition of the net-metering policies even affects the sensitivity of the investment in relation to country discount rate.

Excluding the influence of the discount rate, that is, setting the rate at 10%, it was possible to analyze the impact of the net-metering policies on PV investments. For the evaluated case studies and considering as the base scenario REN nº 482/2012 (EECS = 100%), the approval of Law nº 13.400/2022 (EECS = 72%), on average, reduces 5.77% the IRR and 8.55% the NPV and increases 7.53% the $LCOE$ and 7.91% the DP. However, if AIR nº 003/2019 (EECS = 38%) was approved, on average, it would decrease 12.81% the IRR and 18.93% the NPV and it would increase 18.34% the $LCOE$ and 19.43% the DP. DP and NPV were the indicators most impacted by EECS in percentage terms, followed by $LCOE$ and IRR.

It is important to highlight that the creation of a legal framework for regulating PV distributed generation contributes to the consolidation of the sector, increasing its predictability and bringing certainty to those involved. In Brazil, after the legal framework in 2012, the PV installed power grew from 8 MW to around 36,000 MW nowadays. The growth in solar energy generation is in line with the Sustainable Development Goals (SDGs), in relation to the use of renewable and clean sources.

In countries with a predominance of hydroelectric generation, like Brazil, energy transition contemplating other renewable sources can bring several additional benefits. In these countries, PV systems, for example, can help reduce: (1) the risks related to not meeting energy demand due to the water crisis, (2) the need to activate thermoelectric plants which increases generation costs in the country, (3) electrical losses in energy transmission and distribution systems, and (4) system overload, especially during peak hours.

As can be seen from the results, restricted compensation (for example, EECS = 38%) significantly impacts the profitability of the investment, with a reduction in IRR of more than 10%. On the other hand, allowing compensation of all energy injected into the grid (EECS = 100%), in which the prosumer does not pay for the use of the grid, can harm concessionaires and consumers who have not invested in their own power generation. Thus, a balance when defining the EECS is recommended.

Lastly, it is noteworthy that the 36 evaluated scenarios presented positive results. The worst DP (7.34 years) is considered reasonable by most companies. Therefore, even though the net-metering policies in Brazil show a reduction in the percentages of energy compensation from 2023, investments in PV systems remain viable in the country. This contributes to the growth of both distributed generation and solar source. Moreover, it shows reasonableness of the PV regulation adopted in Brazil.

This study has limitations related to uncertainty of future variables. Although all parameters and assumptions has been justified (such as: adjustment rate of the energy tariff, degradation rate of the PV systems, average monthly generation, etc), they can change. In this case, the mathematical model would provide different results. Besides, the mathematical model does not contemplate externalities of the evaluated system, for example the potential for reducing CO_2 emissions, investments in transmission lines, etc.

As future work, two suggestions are presented. The first is to integrate PV systems to electric vehicles. One way to reduce the emission of polluting gases is through replacing combustion vehicles for electric ones. This strategy is interesting when combined with distributed solar PV. Thus, a study on the viability of electric vehicles, including solar PV generation for recharging, could guide decision-makers, regulatory partied and government towards achieving sustainability goals, such as those described in the Sustainable Development Goals (SDGs). The second suggestion is related to subsidies for the solar energy source. In this paper, net-metering rule in Brazil was evaluated. However, around the world several mechanisms are implemented to encourage investment in solar energy projects; such as net-metering, buy-all sell-all, and net-billing. Therefore, a comparison of how different solar PV subsides work and how net-metering rules are applied in other countries would provide a more comprehensive view of the global landscape of solar PV investments.

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2.2 - Electric vehicles attractiveness in emerging country (Brazil) considering policy and regulation towards energy transition


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Highlights

- Comprehensive TCO model including flex-fuel vehicles and net-metering policies.
- Analysis for comparable pairs and best-selling vehicles in the Brazilian market.
- Focus on light-duty vehicles from entry, compact, medium, and luxury levels.
- Acquisition cost and energy efficiency are the most relevant for EV diffusion.
- EVs still depend on government subsidies to be cost-competitive in Brazil.

Abstract

Transportation sector is largely responsible for global CO_2 emissions, negatively impacting the environment and human health. In developing and emerging economies Electric Vehicles (EVs) market share is still incipient. Therefore, this research evaluates EV attractiveness in relation to Internal Combustion Vehicles (ICVs) for Brazil, an emerging country with a consolidated market of alternative fuels and a regulated system of electricity compensation. The objective is to bring information that can speed up the transition process towards sustainable mobility. The methodology contemplates the development of a comprehensive Total Cost of Ownership (TCO) model, including the country's specificities in terms of biofuels and net-metering. The results show that EVs still depend on government and manufactures subsidies to be cost-competitive in Brazil. Finally, in the last year, the combination of government subsidies (electricity and tax reduction) and strong competitive prices from some manufactures have contributed to boost EV adoption in the country. In this research, the Green Premium (GP) value or “energy transition costs” between ICVs and BEVs, considering medium level automobiles is - R$ 23,000 for comparable and - R$ 73,000 for best-selling data, showing the cost-competitiveness of electric in relation to combustion vehicles in the country.

Keywords

Alternative Fuel; Climate Change; Electric Mobility; Gas Emissions; Sustainable Transportation; Total Cost of Ownership.

1. Introduction

Climate change is a worldwide concern. It refers to long-term shifts in temperatures and weather patterns - resulting in warmer temperatures, intense droughts, water scarcity, severe fires, rising sea levels, flooding, melting of polar ice, catastrophic storms, and declining biodiversity. The main driver of climate change is the Carbon Dioxide (CO_2) one of the Greenhouse Gases (GHG). It comes mostly from the burning of fossil fuels - such as coal, oil, and natural gas. In [1] China, United States, India, European Union, Indonesia, Russian Federation, and Brazil are highlighted as major CO_2 emitters.

In global CO_2 emissions, the power and transport sectors are large contributors [2]. In this context, energy transition and sustainable transport have been promoted in order to achieve low-carbon systems. Energy transition is related to the change in the method of power production, from fossil to clean and renewable source - solar, wind, hydro, and biomass. Sustainable transport, on the other hand, concerns to low or zero emission transportation - including electric and alternative fuel vehicles [3].

As a reminder, Internal Combustion Vehicles (ICVs) are powered by a regular Internal Combustion Engine (ICE) that burns gas, commonly derived from fossil fuel. Electric Vehicles (EVs) are powered, at least in part, by electricity and use a battery to store energy. Plug-in Hybrid Electric Vehicles (PHEVs) use both an ICE and electric motor that can be powered by gas and electricity, respectively. In this case, the battery can be recharged through regenerative braking or external power outlet. Hybrid Electric Vehicles (HEVs) also use both an ICE and electric motor. However, energy stored in batteries are charged exclusively through regenerative braking. Battery Electric Vehicles (BEVs) use only electric motor to power the vehicle and contain batteries which can be charged externally and through regenerative braking. Therefore, EVs contemplate PHEVs, HEVs, and BEVs [4].

Several actions have been adopted globally to mitigate climate change and promote sustainable development. Examples include the Sustainable Development Goals [5], the United Nations Framework Convention on Climate Change [6], and the Paris Agreement [7]. The primary target of these actions is net-zero emissions, aiming to reduce CO_2 emissions to nearly zero.

In Paris Declaration on Electro-Mobility and Climate Change & Call to Action, it was pointed out that the transport sector's contributions to CO_2 emissions grow faster than any other energy end-use sector [8]. In this declaration, International Energy Agency (IEA) indicated that in the case of limiting warming to 2°C or less, at least 20% of the vehicles around the world are required to be electrically driven by 2030. Of these, light-duty vehicles would primarily contribute representing over 100 million cars in 2030 [9].

Global EV Outlook 2023 [9] shows that the stock of BEVs and PHEVs, considering light-duty vehicles, from 2015 to 2022 varied 0.3-13.8 million in China, 0.4-7.8 million in Europe, 0.4-3.0 million in the United States, and 0.2-1.6 million in other regions (including Brazil). This publication also indicates that India and Indonesia, for example, had a notable electromobility boom in 2022. Moreover, Russia is aiming to leverage minerals to develop a battery industry, and for having no less than 10% of car production as EVs in 2030. Brazil was rarely mentioned in this document. This demonstrates that the EV transition in the country has occurred slowly, considering it is a major CO_2 emitter, as previously cited.

According to [10], ICVs lose 64% to 75% of energy, while BEVs lose 15% to 20% of energy during operation. Beyond technological benefits, EVs can contribute to promote decarbonization and energy security, reduce air and noise pollution; improving life quality, public health, and general well-being of people. However, [11] mention that EVs can have emissions during their life cycle when the electricity generated to power EVs is not clean. In Brazil, around 85% of electricity comes from clean and renewable sources – hydro 61.9%, wind 11.8%, biomass 7.2%, and solar 4.4% [12] making EVs a promising solution in the country [13].

Brazil is highly dependent on road transport. It has a well-established biofuels market, based on flex-fuel technology [14]. Flex-fuel vehicles in the country can run on gasoline, ethanol, or a mix of both [15]. However, diesel fuel is the primary source of energy in the transport sector, followed by gasoline, and ethanol. Diesel fuel is a large emitter of GHG and its domestic price has variated due to the international scenarios and national policies. Moreover, the demand for diesel fuel has grown in recent years and is expected to continue growing until 2031[16].

In Brazil, EV sales have grown recently. According to [17], in total 177,358 EVs were sold in 2024, an increase of 89% compared to 2023. By 2030 there will be around 1 million electric and hybrid cars in circulation in the country. In the end of 2024 EV market share reached 5% [18]. [19] defines the "tipping point" for EVs adoption as the moment when 5% of all new vehicle sales are EVs. Despite the growth, this number is still low due to high purchase price, lack of charging infrastructure, limited range, long recharging time, high electricity tariff, low resale value, technological uncertainties, absence of framework regulatory and public policies [9, 20, 21].

[22] mentions EV purchase price as the most relevant variable for the diffusion of electric mobility in Brazil. Purchase price is an important input for calculating the Total Cost of Ownership (TCO). TCO is an economic evaluation model that can be used as tool to compare different products. In the context of transport electrification, it has been employed to compare ICVs and EVs. TCO provides the Net Present Value (NPV) of the sum of all vehicle costs, considering its entire life cycle - acquisition, operation, and disposal [23]. Therefore, it is a useful method to help a rational consumer in decision making about which vehicle to acquire. Previous studies have suggested that providing consumers with TCO data may increase EV adoption [24]. The importance of the TCO for EV expansion has also been highlighted in [11, 25, 26], and others.

From [27], several studies have been developed to compare different propulsion systems through TCO. However, [28] shows that there is no consensus on the appropriate scope of costs and benefits to be quantified in TCO studies. [29] discusses that the TCO model differ depending on the research's proposed point of view. [24] presents a review of 30 comparative TCO studies published between 2017 and 2022, they conclude that there is still no-uniform list of components that should be included in TCO analysis. According to [23], since TCO models use different parameters and assumptions, there is a lack of consensus concerning the cost-competitiveness of EVs. [30] argues that the debate about if, and under which conditions, BEVs are cost competitive is still open.

Most TCO studies have been conducted in the countries with the highest share of EVs, such as China [28, 31], the European Union [26, 30], and the United States [24]. However, for countries in the early stage of electric mobility, like Brazil, TCO analysis is crucial to support consumers, manufacturers, and policy makers in their decisions. Thus, the next three paragraphs present studies developed in the Brazilian context followed by the literature gap.

[32] analyzes TCO and public health issues in Brazil. TCO for ICVs and similar EVs are compared, considering three small corporate fleets. The scenarios, with and without taxes, contemplate five years and vary according to cost of acquisition, maintenance and operation; frequency of use; and residual value. The results show economic infeasibility of EVs in corporations for the period studied, even though the costs of maintenance and operation are significantly lower.

[33] presents a study about the decarbonization path for the transportation sector in Brazil. TCO is employed to show, for example, the cost parity among flex-fuel, PHEVs, and BEVs. For personal light-duty vehicles three car categories are considered: small, medium, and Sports Utility Vehicles (SUVs). Costs of acquisition, financing, battery replacement, fuel, annual tax, and residual value are cited as the main factors influencing TCO analysis. According to the results, cost parity between flex-fuel and BEVs will be reached in 2035 for small cars, 2031 for medium cars, and 2029 for SUVs.

[11] evaluates life cycle emissions and TCO in the six largest automotive markets: China, the United States, Europe, Japan, India, and Brazil. In relation to Brazil, they mention that: (1) it has the cleanest electricity mix among the six countries, permitting EVs to offer its highest possible decarbonization potential; (2) it has the highest purchase cost, along with India, because the country is not established in terms of EV manufacturing; and (3) it presents more prominent TCO gap since few incentives are offered. In this study, TCO calculation was modeled for three different powertrains (ICVs, PHEVs, and BEVs), considering SUVs and

trying the maximum possible parity in terms of powertrain capacity and driving range. Purchase cost, taxes, incentives, insurance, energy cost, and maintenance cost are the components employed in the calculation. They conclude that EVs are the most expensive option in Brazil, as well as in the other five countries; and PHEVs are the cheapest option in the country, mainly due to the high amount of savings obtained in the energy cost, despite higher purchasing cost.

As can be observed, TCO provides an important information, specific to each country or state, that can contribute to boosting EV transition process. However, few studies have analyzed the TCO in the context of Brazil. Of the three publications described previously, data in [32] may be outdated given the recent technological advances. In [33] the results are presented; but TCO model, parameters, and assumptions are not detailed. TCO analysis in [11] is for electric SUVs, however it would be important to evaluate small and medium sized EVs as well.

Therefore, there is a significative literature gap about EV cost-competitiveness in Brazil. The lack of this information can compromise the country's participation to the global transport electrification process. It is worth to highlight that Brazil has a large automotive market, uses diesel fuel as primary energy source in the transport sector, and produces electricity mostly from clean and renewable sources, favoring EV adoption.

Thus, this paper presents a comprehensive TCO model applied to a range of vehicle's levels and powertrains, considering the Brazilian context. Our research takes into account the vast experience published in the literature on the topic, presenting an analysis that is as complete, accurate, and current as possible. In addition, we describe the regulatory framework, laws, subsidies, and incentives related to electric mobility in the country. Twenty-three scenarios from seven case studies are analyzed. The seven case studies contemplate: (1) comparable pairs - baseline, (2) comparable pairs - changing behavior parameters, (3) comparable pairs - excluding government subsidies, (4) comparable pairs - extreme positive scenario for EVs, (5) comparable pairs - extreme negative scenario for EVs, (6) comparable pairs - changing discount rates, and (7) best-selling vehicles.

As main contribution, this work is the first complete study in Brazil, considering the country's specificities in terms of alternative fuel and electricity credit compensation system. Our analysis contemplates vehicles with biofuel technology, since Brazil has the largest flex-fuel fleet in the world. Moreover, although some studies consider subsidies for electricity, for the best of our knowledge, such subsidies have not been explored in the TCO analysis.

In summary, the uniqueness of our TCO model compared to existing studies is its integration with the Brazilian energy policies in the mathematic formulation. For example, Equations (5-8) consider vehicles with biofuel technology, while Equation (9) refers to the net-metering system enforced in the country. Therefore, our approach in the methodology brings more accurate results for the studies and assists countries with similar characteristics to Brazil in terms of energy transition process. Our TCO model can be adapted to any other country or state if the relevant data is available. The results can assist consumers, manufacturers, and policy makers; guiding their decisions, marketing strategies, and efficient use of public resources; respectively.

The remainder of this article is structured as follows: Section 2 describes the regulations for clean vehicles. Section 3 shows the development of the mathematical model based on the TCO. Section 4 presents the data, parameters, and scenarios employed. Section 5 shows the results and discussion considering comparable and best-selling vehicles. Finally, Section 6 brings conclusions, limitations, and future works.

2. Regulations for Clean Vehicles

The introduction of new technologies usually encounter resistance in markets due to the presence of consolidated sociotechnical systems that support already established technologies [34]. However, governments can play an important role in guiding transition and stimulating technological development. In this sense, the Brazilian context is interesting since the country has experience with the diffusion of alternative fuel. The National Alcohol Program (Pró-Álcool), established by Decree n° 76.593/1975, was an initiative of the Federal Government with the purpose of promoting the production of ethanol through sugarcane to replace gasoline. In 2003, the rapid adoption of flex-fuel technology in vehicles enabled a widespread of the biofuel [35].

According to [36], the diversity of challenges around electric mobility suggests the need to implement a wide range of instruments, policies, and regulations aimed at creating an environment favorable to the dissemination of EVs. Such instruments may fall under some general categories, according to the main scope of action (direct or indirect promotion). Direct promotion is done through instruments of monetary nature (ex: tax exemption) and non-monetary (ex: driving in permitted areas); regulatory nature (ex: normative support); and structural nature (ex: charging infrastructure). On the other hand, indirect promotion is done through instruments that create favorable context, such as policy instruments (ex: goal for CO_2 emission); improving infrastructure (ex: restructuring the electricity sector); social initiatives (ex: popularization, awareness, and acceptance of EVs).

Direct and indirect promotion can be done through different spheres of government: federal, state, and municipal. For example, incentives for purchasing EVs are specific to governments in national and state spheres, while exemption for access in areas with restriction are often implemented at the municipal sphere. This separation reflects the distribution of skills between spheres of government [36].

In Brazil, specific regulations on electric mobility are still under development. For this reason, Table 1 presents some of the main policies related to the evolution of the automotive industry towards the development of a clean and sustainable transportation at federal level. This table lists important government programs, such as Proconve, Pronar, Promot, PBE-V, RenovaBio, Rota 2030, and MOVER.

Rota 2030 [37], for example, is a federal program of 2018 which reduces purchase taxes for customers and provides tax credits over five years for carmakers that invest in new technologies for the manufacture of more efficient and less polluting vehicles. Due to the success of this program, in Dec/2018 Toyota Brazil announced the development of the world's first commercial hybrid electric vehicle with flex-fuel engine capable of running with electricity and ethanol or gasoline fuel.

Table 1 - History of policies aimed at clean and sustainable transportation in Brazil (chronological order)

Policy	Description	Reference
Res. nº 18/1986	Created the Air Pollution Control Program by Motor Vehicles (Proconve). European emission standards used as a reference.	[38]

Res. nº 5/1989	Created the National Air Pollution Control Program (Pronar) with the aim of limiting the levels of pollutant emissions by sources.	[39]
Law nº 8.723/1993	Provided for the reduction of pollutant emissions from motor vehicles requiring manufacturers to create more sustainable vehicles, engines, and fuels.	[40]
Law nº 9.991/2000	Established that companies must annually apply a percentage of net operating revenue (0.5% - 1%) in R&D projects.	[41]
Law nº 10.295/2001	Known as the Energy Efficiency Law, provided for the National Policy for Conservation and Rational Use of Energy. It establishes maximum levels of energy consumption or minimum energy efficiency of machines.	[42]
Res. nº 297/2002	Created the Air Pollution Control Program for Motorcycles and Similar Vehicles (Promot). To complement Proconve.	[43]
Dec. n° 6.259/2007	Created Brazilian Technology System (Sibratec). Aimed to support technological development of EV related topics through the promotion of R&D activities.	[44]
Ord. nº 391/2008	Created the Brazilian Labeling Program (PBE-V) aimed to standardize and record the level of energy efficiency of each labeled vehicle.	[45]
Law nº 12.187	National Policy on Climate Change (PNMC)	[46]
Law nº 12.715/2012, 12.996/2014	Created Inovar-Auto, a program to encourage vehicle technology innovation.	[47]
Res. nº 86/2014, 97/2015, 27/2016, 97/2018	Established by the Chamber of Foreign Trade (Camex), determines the reduction from 35% to 0% of the Import Tax rate for electric or fuel cell cars.	[48]
CP nº 002/2016	Public Consultation about the opinion of distributors in relation to EVs.	[49]
AP nº 029/2017	Public Hearing aimed to reduce possible regulatory barriers regarding the charging infrastructure of EVs.	[50]
Law 13.576/2017	Created National Biofuels Policy (RenovaBio) with the objective of expanding the production of biofuels in Brazil seeking to reduce GHG emissions and contribute to country's commitments under the Paris Agreement.	[51]
Dec. nº 9.442/2018	Reduced the Industrialized Products Tax (IPI) rate on EVs from 25% to 7% and on hybrid vehicles from 25% to 20%. Repealed by Decree no 11.158/2022.	[52]
Res. nº 819/2018	Established by ANEEL, regulates recharges of EVs. Revoked by RN nº 1.000/2021.	[53]
Call nº 022/2028	Call for projects that encompasses the “Development of Solutions in Electric Mobility Efficiency”.	[54]
Law nº 13.755/18 Decree nº 9.557/18	Created Rota 2030 that defined rules for the manufacture of cars produced and sold in Brazil over 15	[55]

	years. Especial emphasis to Work Group 7 – Hybrid and EVs.	
Ord. nº 2.519/2019	Established by the Special Secretariat for Productivity, Employment and Competitiveness (SEPEC), defines priority automotive programs.	[56]
Law nº 14.000/2020	Amended Law 12.587/2012 and determined that municipalities must prepare and approve Urban Mobility Plan.	[57]
Res. nº 1.000/2021	Consolidates the rights and duties of electricity consumers and establishes the Rules for the Provision of the Public Electricity Distribution Service. The provisions of the installation of EV chargers are in Chapter V.	[58]
Res. nº 13/2023	The resources raised in the context of Rota 2030 are applied in programmatic lines defined by the Management Council of the resources of the program for selecting priority projects.	[37]
MP nº 1.175/2023	Provided for sponsored discount mechanism for the acquisition of sustainable vehicles.	[59]
MP nº 1.205/2023	Establishes the Green Mobility and Innovation Program - MOVER Program.	[60]
Res. nº 532/2023	Provided that EVs, hybrids and plug-in hybrids purchased outside the country will gradually be subject to import tax.	[61]

The main source for mapping the information on EV policies globally is the International Energy Agency (IEA). IEA publishes reports through a multi-government policy forum dedicated to accelerating the introduction and adoption of EVs worldwide, named Electric Vehicles Initiative (EVI). IEA acts as coordinator, supporting sixteen country members. Brazil is not a participating country, but it is associated with the initiative [62]. For this reason, the information in Table 1 is obtained by IEA's reports and complemented with literature (dissertations, theses, and articles), agency websites, and public or private organizations involved in the promotion of EVs.

Historically, countries began the development of EV market due to energy security, environmental/health issues, and need for innovation. These historical issues are important justifications for investments, subsidies, programs, and plans for action. In the case of Brazil, these elements were tackled with other technological options, for example, bioethanol adoption [36].

Norway is a world-leading country when it comes to electrifying passenger vehicle. The Norwegian Parliament has decided on a national goal that all new cars sold by 2025 should be zero-emission. The reasons for the high penetration of EVs in Norway are related to the incentives for promoting purchase and ownership of EVs. Besides, there are also incentives making EVs more convenient in daily use by providing, for example, recharging infrastructure and parking spaces [63].

As mentioned previously, few actions have been observed in Brazil specifically for EVs, although as Table 1 many general actions aimed at clean and sustainable transportation have been done. The initiatives in the country for EV purchase and ownership have been restricted to tax reduction on Industrialized Products (IPI) and Motor Vehicle Ownership (IPVA). In addition to tax incentives, EV owners can have other benefits, such as free or discounted parking areas, use of exclusive lanes, and discounts on tolls.

The import tax applicable to EVs were zero since 2015 through the List of Exceptions to the Common External Tariff (LETEC). However, one of the most recent policies related to electric mobility in Brazil, Resolution nº 532/2023, established that from January of 2024 EVs purchased outside of Brazil will gradually be subject to import tax. The resolution establishes a gradual resumption of tariffs and creates quotas for exemption of imports until 2026 (Table 2). According to the federal government, the reestablishment of taxation aims to develop the national automotive sector and accelerate the decarbonization process of the Brazilian fleet [64].

Table 2 - Import schedule, tax exemption and quotas [64]

Propulsion System	Jan/2024	Jul/2024		Jul/2025		Jul/2026	
	Tax [%]	Tax [%]	Quota million [US$]	Tax [%]	Quota million [US$]	Tax [%]	Quota million [US$]
BEV	10	18	283	25	226	35	141
PHEV	12	20	226	28	169	35	75
HEV	15	25	130	30	97	35	43

Although there are ongoing actions within the scope of federal sphere towards clean and sustainable vehicles, the absence of a basic framework hurdles for broader adoption of EVs [65]. Establishing electrification goals would ensure greater security and predictability for industry investments [66]. Besides, international experience has shown that the reduction of EVs initial cost is important for boosting adoption. Furthermore, according to [67], lower TCO including lower maintenance and fueling costs are key drivers of EV sales.

3. Methodology - Total Cost of Ownership (TCO)

The TCO model developed in this research is supported by an extensive literature review. Different formulations, components, and assumptions were identified and are mentioned in this section. The TCO of a vehicle covers all costs of its lifetime ($n = 1 \ldots N$), Initial Costs (IC) and Annual Costs (AC), subtracting its Residual Value (RV) at the end of the period (N). For a better understanding of the following paragraphs, Table 3 shows an overview of the data and equations employed in this research for the mathematical formulation of the TCO in Equation (1). All of them are explained and justified in the sequence.

Table 3 - Data and equations for TCO calculation.

Total Cost of Ownership Equation (1)	
Initial Costs Equation (2)	Manufacturer's Suggested Retail Price (-) Retailer's Discounts Taxes and Fees (-) Subsidies for Vehicle Home Charger

	(-) Monetary Incentives for Home Charger		
Annual Costs Equation (3)	Energy Costs Equation (4)	Energy Price Equation (5)	Percentage of Electricity Charged at Home and Public Area Electricity Price for Home and Public Charge Rate of Change in Electricity Prices Percentage of Gasoline and Ethanol Usage Gasoline and Ethanol Price Rate of Change in Fuel Prices Percentage of Electricity Usage
		Annual Vehicle Kilometers Travelled	
		Energy Consumption Equation (6), (7), (8)	Consumption-Adjustment Factor Percentage of City and Highway Trip Electricity Consumption in City and Highway Area Fuel Consumption in City and Highway Area Gasoline and Ethanol Consumption in City and Highway Area
	(-) Annual Subsidies for Electricity Equation (9)		Percentage of Electricity Charged at Home Electricity Price for Home Charge Rate of Change in Electricity Prices Net-Metering Policy Annual Vehicle Kilometers Travelled Energy Consumption
	Insurance Costs Equation (10)		Manufacturer's Suggested Retail Price Annual Depreciation Rate Insurance Rate
	Maintenance and Repair Costs Equations (11) e (12)		Manufacturer's Suggested Retail Price National Consumer Price Index Maintenance and Repair Rate Battery Cost Rate of Change in Battery Prices
	Annual Taxes and Fees Equation (13)		Manufacturer's Suggested Retail Price Annual Depreciation Rate Ownership Tax Certificate of Registration and Licensing National Consumer Price Index Mandatory Vehicle Insurance
	(-) Annual Subsidies for Vehicle Equation (14)		Maintenance and Repair Costs Subsidized by Manufactures
(-) Residual Value Equation (15)	Manufacturer's Suggested Retail Price Annual Depreciation Rate		

Since the TCO formulation contemplates future costs, the investor's time value of money is taken into account. Net Present Value (NPV) method is employed to estimate the current value of future costs, considering a discount rate (r_d) and the time when the costs occur (n); as in [23, 24, 28, 29, 30, 31, 68].

The current TCO of a vehicle, contemplating the NPV method, can be written according to Equation (1). In this equation, it is possible to distinguish three phases, one for each term of the TCO: acquisition (IC), operation (AC), and disposal (RV). These three phases represent the costs associated with the vehicle in the different stages of ownership.

$$TCO_i = IC_i + \sum_{n=1}^{N} \left[\frac{AC_{i,n}(VKT)}{(1 + r_d)^n} \right] - \frac{RV_{i,N}}{(1 + r_d)^N} \tag{1}$$

where:

i	type of the vehicle: ICV, HEV, PHEV, or BEV;
TCO_i	total cost of ownership for vehicle type i [R$];
IC_i	initial costs for vehicle type i [R$];
n	specific number of a period [year];
N	total number of periods [years];
$AC_{i,n}$	annual costs for vehicle type i in the period n [R$];
VKT	annual vehicle kilometers travelled [km/year];
r_d	annual discount rate [%];
$RV_{i,N}$	residual value for vehicle type i in the last period, N [R$].

1) Initial Costs (IC)

Initial Costs (IC) include all expenses to acquire the vehicle, Equation (2). Some examples are Manufacturer's Suggested Retail Price ($MSRP$), taxes, registration fees, plate number, accessories, etc. Of these, $MSRP$ is the largest share of the TCO. $MSRP$ includes the partial tax exemption on Industrialized Products (IPI), computed as Table 2. For BEVs and PHEVs, the costs for home charger (equipment, installation, and permit) can also be considered. Possible retailer's discounts, subsidies for vehicle (from federal/state/local government or manufacture), and any monetary incentives for home charger should be subtracted from the Initial Costs (IC).

$$IC_i = MSRP_i - RD_i + TF_i - SV_i + HC_i - MIHC_i \tag{2}$$

where:

IC_i	initial costs to acquire the vehicle type i [R$];
$MSRP_i$	manufacturer's suggested retail price for vehicle type i [R$];
RD_i	retailer's discounts for vehicle type i [R$];
TF_i	taxes and fees for vehicle type i at the purchase time [R$];
SV_i	subsidies for vehicle type i at the purchase time [R$];
HC_i	home charger costs (equipment, installation, and permit) for i = BEV or PHEV [R$];
$MIHC_i$	monetary incentives for home charger for i = BEV or PHEV [R$].

2) Annual Costs (AC)

Annual Costs (AC) correspond to the sum of all recurrent expenses in every year $n \in [1, N]$ during the ownership period, Equation (3). For example, costs with energy (fuel and electricity), insurance, maintenance and repair are annual; as well as some taxes and fees. As for the Initial Costs (IC), subsidies for electricity and subsidies for vehicle (from federal/state/local government or manufacture) must be subtracted of the Annual Costs (AC).

$$AC_{i,n}(VKT) = EC_{i,n} - ASE_{i,n} + INC_{i,n} + MRC_{i,n} + ATF_{i,n} - ASV_{i,n} \tag{3}$$

where:

$AC_{i,n}$	annual costs for vehicle type i in the period n [R$];

$EC_{i,n}$ energy costs for vehicle type *i* in the period n [R$], calculated from fuel [R$/l] and/or electricity [R$/kWh] prices as function of VKT;
$ASE_{i,n}$ annual subsidies for electricity, considering i = BEV or PHEV in the period n [R$];
$INC_{i,n}$ insurance costs for vehicle type *i* in the period n [R$];
$MRC_{i,n}$ maintenance and repair costs for vehicle type *i* in the period n [R$];
$ATF_{i,n}$ annual taxes and fees for vehicle type *i* in the period n [R$];
$ASV_{i,n}$ annual subsidies for vehicle type *i* in the period n [R$].

2.1) Energy Costs (EC)

Energy costs refers to fuel and/or electricity expenses required to operate the vehicle during its lifetime. It represents a significant portion of the TCO. Energy Costs (EC) are calculated from the product of energy price, annual VKT, and energy consumption; as shown in Equation (4).

In order to estimate future costs probabilistic and non-probabilistic approaches can be employed. A few studies apply probabilistic methods in the TCO model, for example, [69, 70]. This research uses a non-probabilistic approach, as most TCO models. In this case, future costs are calculated from the initial costs and an inflation or growth rate.

$$EC_{i,n} = EPrice_{i,n} * VKT_{i,n} * EConsu_{i,n} \tag{4}$$

where:
$EPrice_{i,n}$ energy price for vehicle type i in the period n: fuel [R$/l] and/or electricity [R$/kWh];
$EConsu_{i,n}$ energy consumption for vehicle type i in the period n: fuel [l/km] and/or electricity [kWh/km].

For energy price, first factor of Equation (4), some authors adopt historic average value. In this analysis, electricity and fuel prices are adjusted annually, through r_e and r_f rates, as [31].

Besides, several TCO analysis do not differentiate the electricity price between home and public charging for BEVs and PHEVs. In this research, the weighted average of the electricity price is computed, considering the charging percentage at home ($\alpha_{i,n}$) and public place ($1-\alpha_{i,n}$), according to [26, 71].

Regarding ICVs and HEVs, the weighted average is also adopted for the most used fuels by light-flex vehicles in the Brazilian context, gasoline and ethanol. Thus, the usage percentage of gasoline ($\mu_{i,n}$) and ethanol ($1-\mu_{i,n}$) is included in the formulation.

In addition, since PHEVs can run on fuel and electricity, energy price is calculated considering the usage percentage of electricity ($\beta_{i,n}$) and fuel ($1-\beta_{i,n}$), as [30]. Equation (5) presents these specificities in the energy price calculation for BEVs (electricity), ICVs/HEVs (fuel), and PHEVs (electricity and fuel).

$$EPrice_{i,n} = \begin{cases} \left[\alpha_{i,n} * HElecPrice + \left(1-\alpha_{i,n}\right) * PElecPrice\right] * (1+r_e)^n & \textit{for BEV} \\ \left[\mu_{i,n} * GasolPrice + \left(1-\mu_{i,n}\right) * EthanPrice\right] * \left(1+r_f\right)^n & \textit{for ICV and HEV} \\ \beta_{i,n} * EPrice_{BEV,n} + \left(1-\beta_{i,n}\right) * EPrice_{ICV,n} & \textit{for PHEV} \end{cases} \tag{5}$$

where:

$\alpha_{i,n}$ percentage of electricity charged at home for i = BEV or PHEV in the period n [%];
$HElecPrice$ electricity price for home charge [R$/kWh];
$PElecPrice$ electricity price for public charge [R$/kWh];
r_e rate of change in electricity prices [%];
$\mu_{i,n}$ percentage of gasoline usage for i = ICV, HEV, or PHEV in the period n [%];
$GasolPrice$ gasoline price [R$/l];
$EthanPrice$ ethanol price [R$/l];
r_f rate of change in fuel prices [%];
$\beta_{i,n}$ percentage of electricity usage for i = PHEV in the period n [%].

Concerning the third factor of Equation (4), energy consumption can be affected, for example, by speed patterns. Therefore, city and highway consumption are distinguished in this analysis, through the percentage of city ($\theta_{i,n}$) and highway ($1-\theta_{i,n}$) trip, as [30].

Also, extreme temperatures can compromise the battery performance of BEVs and PHEVs. Thus, an adjustment factor for consumption ($\gamma_{i,n}$) is applied which reflects the difference between nominal and real values [31]. Equations (6), (7), and (8) show these details for the third factor of Equation (4).

$$EConsu_{i,n} = \begin{cases} \gamma_{i,n} * [\theta_{i,n} * CElecConsu_{i,n} + (1-\theta_{i,n}) * HElecConsu_{i,n}] & \textit{for BEV} \\ \theta_{i,n} * CFuelConsu_{i,n} + (1-\theta_{i,n}) * HFuelConsu_{i,n} & \textit{for ICV and HEV} \\ \beta_{i,n} * EConsu_{BEV,n} + (1-\beta_{i,n}) * EConsu_{ICV,n} & \textit{for PHEV} \end{cases} \tag{6}$$

$$CFuelConsu_{i,n} = \mu_{i,n} * CGasConsu_{i,n} + (1-\mu_{i,n}) * CEthConsu_{i,n} \tag{7}$$

$$HFuelConsu_{i,n} = \mu_{i,n} * HGasConsu_{i,n} + (1-\mu_{i,n}) * HEthConsu_{i,n} \tag{8}$$

where:

$\gamma_{i,n}$ consumption-adjustment factor for i = BEV or PHEV in the period n [%];
$\theta_{i,n}$ percentage of city trip for vehicle type i in the period n [%];
$CElecConsu_{i,n}$ electricity consumption in city area for i = BEV or PHEV in the period n [kWh/km];
$HElecConsu_{i,n}$ electricity consumption in highway area for i = BEV or PHEV in the period n [kWh/km];
$CFuelConsu_{i,n}$ fuel consumption (gasoline or ethanol) in city area for i = ICV, HEV, or PHEV in the period n [l/km];
$HFuelConsu_{i,n}$ fuel consumption (gasoline or ethanol) in highway area for i = ICV, HEV, or PHEV in the period n [l/km];
$CGasConsu_{i,n}$ gasoline consumption in city area for i = ICV or HEV in the period n [l/km];
$CEthConsu_{i,n}$ ethanol consumption in city area for i = ICV or HEV in the period n [l/km];

$HGasConsu_{i,n}$ gasoline consumption in highway area for i = ICV or HEV i in the period n [l/km];

$HEthConsu_{i,n}$ ethanol consumption in highway area for i = ICV or HEV in the period n [l/km].

2.2) Annual Subsidies for Electricity (ASE)

Annual subsidies for electricity can be offered on the charging costs at home or public places. It is usually provided through a rebate, discount, or free item. According to [25], subsidies for electricity are an effective policy specially for countries with high fuel prices and low EV acceptance levels.

In Brazil, subsidies for electricity are related to climate change discussions that drive energy transition. The objective is to promote distributed generation from renewable energy sources. For this, compensation mechanisms of energy, such as Net-Metering (NM), are available for solar photovoltaic system owners. In this case, the electricity added to the grid can be credited back [72].

Thus, annual subsidies for electricity are subtracted from the energy costs of BEVs and PHEVs. They are computed as a percentage discount on the electricity price at home. The percentage discount depends on the date the consumer joins the net-metering system, as explained in the next section. Equation (9) shows annual subsidies for electricity, considering the NM policy in force nowadays.

$$ASE_{i,n} = [(\alpha_{i,n} * \ HElecPrice) * (1 + r_e)^n] * NM_{i,n} * VKT_{i,n} * EConsu_{i,n} \tag{9}$$

where:

$NM_{i,n}$ net-metering policy or percentage discount on the electricity price for i = BEV or PHEV in the period n [%].

2.3) Insurance Costs (INC)

In many countries vehicle insurance is mandatory in order to legally drive on roads, for example, United States. In other countries, such as Brazil, car insurance is not required, but strongly recommended. Usually, insurance costs vary depending on the characteristics of the vehicle (MSRP, powertrain, and type of use), owner (age, driving history, and residential area), and company (commercial strategy).

[24] consider the vehicle's MSRP, powertrain, mileage, and location for insurance costs. [73] use real-life costs extracted from insurance policies of the evaluated vehicles. [68] charge the insurance at the rate of 4% of the vehicle's value in the first year and 3% in the following years.

Some authors compare insurance costs for EVs and ICVs. [74] assume that BEVs insurance is approximately 20-30% higher than ICVs insurance. [11] adopt average insurance costs for each analyzed country, mentioning that BEVs are around 20% higher than ICVs and HEVs. [71] assume an average insurance cost and fixed over time for ICVs and BEVs, of which for BEVs it is around 13% higher than for ICVs.

Several researches do not consider insurance cost in the TCO formulation, assuming it is similar for ICVs and BEVs. [23, 25, 31] are some examples.

In this study, insurance costs are computed as a percentage of the vehicle's market value, as Equation (10). According to [75], in Brazil, car insurance for BEVs is between 10% and 20% more expensive than for similar ICVs. Therefore, the insurance rate (ri) depends on the vehicle type i.

$$INC_{i,n} = [MSRP_i * (1 - \varphi_{i,n})^n] * ri_i \quad (10)$$

where:

$\varphi_{i,n}$ annual depreciation rate for vehicle type i in the period n [%];

ri_i insurance rate for vehicle type i [%].

2.4) Maintenance and Repair Costs (MRC)

Maintenance and repair are necessary to maintain the vehicle in operation during its lifetime. These costs depend on the distance travelled and vehicle type. Normally, BEVs have lower service costs than ICVs because of absence of engine, regenerative braking, fewer moving parts and fluids; that means less components to wear out, gaskets to replace, valves to clog up, oil to change, etc.

In [11] maintenance and repair costs are calculated as a percentage of the TCO. [23, 76] consider the annual VKT for such costs. Maintenance and repair costs for BEVs corresponds to a percentage of these costs for similar ICVs in [30] - 70%, [28] - 60%, [71, 31] - 50%. [24, 68] follow the service schedule recommended by the manufacturer in vehicle owner's manuals for maintenance routine and parts replacements.

In this analysis, maintenance and repair costs are calculated as a percentage of the $MSRP$, updated annually according to National Consumer Price Index (IPCA), as Equation (11). The percentage rate (rm) is estimated from the relation between maintenance values and $MSRP$, available on the manufacturer's website, considering the annual VKT adopted. Since BEVs maintenance and repair are usually lower than for similar ICVs, the percentage rate (rm) depends on the vehicle type i.

$$MRC_{i,n} = [MSRP_i * (1 + IPCA)^n] * rm_i \quad (11)$$

where:

$IPCA$ national consumer price index [%];

rm_i maintenance and repair rate for vehicle type i [%].

The most important technological advancement for EVs related to TCO refers to battery system, including energy density and charging speed. EV battery prices are expected to fall due to a continued downturn in metal and component prices, economies of scale, and adoption of lower-cost lithium-iron-phosphate (LFP) batteries. For BEVs and PHEVs battery replacement costs should be considered in the maintenance and repair expenses, due to the battery degradation. This study assumes that the battery replacement will occur in 8th year, after the warranty expires, as [29]. Therefore, for BEVs and PHEVs, when $n = 8$, Equation (11) is re-written as Equation (12). In this new equation, battery cost (BC) and its annual adjustment (r_b) is included in the MRC calculation.

$$MRC_{i,n} = [MSRP_i * (1 + IPCA)^n] * rm_i + BC_i * (1 - r_b)^n \quad \textit{for BEV and PHEV (n=8)} \tag{12}$$

where:

BC_i battery cost for i = BEV or PHEV [R$];
r_b rate of change in battery prices [%].

2.5) Annual Taxes and Fees (ATF)

Recurring taxes and fees are annual costs set by the government that have to be paid in order to legally own and drive vehicles on roads. ATF can be charged at local, state, or federal level.

Usually, annual taxes on vehicle depend on its type and age, for example, in Thailand [29]. In Korea, vehicle's taxes depend on the travelled distance - the longer, the more expensive. Some countries do not charge annual taxes on vehicles, such as Tanzania [68].

Since TCO provides an important information specific to each country or state, this mathematical model focuses on subsidies, regulations, and policies considering the Brazilian context. In Brazil there are three annual taxes and fees related to the vehicle named as Motor Vehicle Ownership Tax (IPVA), Annual Licensing Certificate (CRLV), and Mandatory Insurance for Personal Damage Caused by Land motor Vehicles (DPVAT); [77]. In addition to IPI and ASE mentioned before, the government policies to encourage the purchase and ownership of EVs consider $IPVA$.

IPVA is charged by states as a percentage of the vehicle's market value. This fee is intended to finance public services such as health, education, safety, and road infrastructure. For EVs, some Brazilian states offer IPVA exemption, discount or partial refund.

CRLV is the vehicle's certificate of license that must be renewed every year. It ensures that the vehicle complies with safety and environmental standards and can be driven on roads. CRLV varies depending on the state. It is updated annually, in this paper based on National Consumer Price Index (IPCA).

DPVAT is the Brazilian minimum third-party insurance for personal injury caused by road vehicles. It was established by federal Law nº 6194/1974. DPVAT guarantees assistance to victims of accidents (drivers, passengers, or pedestrians) on Brazilian roads. Since 2021 it is not mandatory, however there is a law project in the government for the return of this tax.

Equation (13) shows the calculation of annual taxes and fees; considering IPVA, CRLV, and DPVAT.

$$ATF_{i,n} = [MSRP_i * \left(1 - \varphi_{i,n}\right)^n] * IPVA_i + CRLV * (1 + IPCA)^n + DPVAT \tag{13}$$

where:

$IPVA_i$ ownership tax for vehicle type i [%];

$CRLV$ cost for vehicle's certificate of registration and licensing [R$];
$DPVAT$ cost for mandatory vehicle insurance [R$].

2.6) Annual Subsidies for Vehicle (ASV)

Annual subsidies for vehicles can be associated to the first or second phase of the ownership period: acquisition or operation. ASV can come from federal/state/local government or manufacture. Subsidies related to the first phase, acquisition time, are applicable directly and one-time. Sales tax exemptions, purchase subsidies (tax credits or rebates), and reduction of registration fees are some examples. These subsides are contemplated in Equation (2).

Other subsidies refer to the second phase, operation time, occurring every year. Some of these subsidies are not monetary, such as preferential lane access or parking, and free circulation of EVs in cities with political restrictions for traffic and pollution control. Annual monetary subsidies include full or partial exemption of annual taxes, fees, and licenses. These subsidies are considered in sub-section 2.5, related to Equation (3).

At this moment, in Brazil, some manufactures offer free maintenance service for five years or up to a determined number of kilometers travelled (whatever happens first), that means, during the first five years of the ownership period considered in this study. For vehicles from these manufactures, the annual subsidies correspond to maintenance and repair costs, when $n = 1, 2, 3, 4, and\ 5$; as Equation (14).

$$ASV_{i,n} = MRC_{i,n} \qquad for\ n = 1, 2, 3, 4, and\ 5 \tag{14}$$

3) Residual Value (RV)

Residual Value (RV) of a vehicle is an estimative of how much it will be worth at the end of ownership period (N) after depreciation over time. Vehicle depreciation is affected by several factors, such as segment, brand, model, VKT, maintenance cost, time of use, and propulsion system. In the EVs case, battery longevity, charging infrastructure availability, and electricity price also impact the depreciation rate.

EVs are known to depreciate faster than ICVs mainly due to the technological improvements and market dynamic. For annual depreciation rate, [29] assume 7-12% depending on powertrain. [68] adopt 15% for ICVs and 17-21% for EVs. [23] use 18.57% for ICVs and 24.43% for EVs. In [26], depreciation is calculated as a constant annual cost.

Some authors estimate the residual value of a vehicle as a direct percentage of $MSRP$. For example, [78] adopt 5% of $MSRP$ as residual value for ICV, PHEV, and BEV; considering an ownership period of fifteen years. For a lifetime of ten years, [28] employs 7% of $MSRP$ for ICVS, 5% of $MSRP$ for PHEVs, and set 0 as residual value for BEVs; justifying that the battery capacity of BEVs drops to below 70% of original capacity.

Equation (15) shows the calculation considered in this study for residual value of a vehicle in the last ownership period (N). It contemplates the vehicle's $MSRP$ and an annual depreciation rate ($\varphi_{i,N}$).

$$RV_{i,N} = MSRP_i * (1 - \varphi_{i,N})^N \tag{15}$$

where:

$\varphi_{i,N}$ annual depreciation rate for vehicle type i in the last period N [%].

4. Vehicles Data, Parameters, and Scenarios

In this section, data and parameters employed in the mathematical model for TCO calculation are described. The criteria used to obtain each input data is specified in detail. The sources are mainly official government agencies, high-quality papers published in reputable journals, and trusted company websites. When appropriate, the acquisition method of data includes a comparison with the information utilized by authors from relevant papers in the same area. This way it is possible to ensure the quality and reliability of the information.

Vehicles Data

The Brazilian traffic code classifies automobiles by traction (self-propulsion, human, animal, or trailer), function (passenger, cargo, mixed, competition, power, special, or collection), and type (official entity, diplomatic representation, private, rental, or learning) - [59]. This paper focuses on self-propulsion, passenger, and private vehicles.

Regarding self-propulsion, more than 80% of the market share is composed by flex-fuel ICVs, running on gasoline and/or ethanol [79]. In this context, and considering the growing interest in EVs, flex-fuel ICVs and HEVs, as well as PHEVs and BEVs, are analyzed. In relation to function, the choice for passenger vehicle is justified by its large consumer base. A total of proximally 2.1 million new vehicles were registered in 2022, of these, over 1.5 million were for passengers [80]. Lastly, since this paper focuses on decision making of consumers, private vehicles are studied.

Table 4 shows comparable vehicles of extreme propulsion systems (ICVs and BEVs) contemplating all levels (entry, compact, medium, and luxury). The availability of vehicles of the same model, from the same manufacture, with different propulsion systems is low in Brazil. Renault, Peugeot, and BMW are some of the few manufactures that present such vehicles. In Table 4, BMW vehicles are the only with no maintenance data, since the manufacture does not publish this information on its website.

Tables 5-8 show best-selling vehicles of the four propulsion systems (ICVs, HEVs, PHEVs, and BEVs) contemplating, whenever possible, different levels (entry, compact, medium, and luxury). The availability of EVs is still low in Brazil. Therefore, similar vehicles in terms of size, features, and price are chosen. Sport Utility Vehicles (SUVs) are prioritized due to popularity and growth in sales - the segment accounted for over 40% of sales in 2023 [81]. For ICVs, the vehicles chosen are the best-selling SUVs in the compact, medium, and luxury levels. In 2023, the leaders by unit sold were: Volkswagen T-Cross (72,440), Jeep Compass (59,106), and Jeep Commander (19,874); according to [81]. For EVs, all best-selling manufactures are represented in the tables. In 2023, the leaders by unit sold were: Toyota (21,042), BYD (17,943), Chery (11,835), GWM (11,473), and Volvo (8,179); as [65]. The data for the best-selling EVs in Brazil is combined meaning that a vehicle, such as the Toyota RAV4 and GWM Haval H6 may have HEV and PHEV variants, however salles number is not separated by propulsion system. For this reason, salles figures are shown as total units sold by manufactures, not by propulsion systems or vehicles. At least one vehicle from each brand is represented.

Data related to the manufacture, model, MSRP, consumption, and maintenance are presented in Tables 4-8. For PHEVs and BEVs, battery capacity and price are also presented. MSRP corresponds to the price announced on the manufacturer’s website in April/2024. For models with different versions, the average price was adopted. Official consumption data were obtained from the Brazilian Vehicle Labeling Program [45]. For PHEVs and BEVs, this program presents consumption information in kilometer per equivalent liters (km/le). Maintenance data corresponds to the sum of the first five scheduled check-ups from the manufacturer's website in April/2024. Battery capacity is available on the technical sheet of each vehicle on the manufacture's website in April/2024. The cost to replace a battery depends on the size, power capacity, and vehicle model. According to [82], the average price of battery is 139 $/kWh in 2023. This corresponds to 685.27 R$/kWh, considering 1 dollar = 4.93 reais from the historical average of Abril/2023-2024 [83].

Table 4 - Comparable pairs

Level	Entry - Renault		Compact - Peugeot		Medium - Peugeot		Luxury - BMW	
Vehicle	Kwid	E-Kwid	208	E-208	2008	E-2008	X1	iX1
MSRP [R$]	75,000	140,000	89,166	236,000	135,000	170,000	300,000	360,000
Ethanol city [km/l]	10.8	-	8.6	-	7.7	-	10.9	-
Ethanol highway [km/l]	11.0	-	10.0	-	8.9	-	13.1	-
Gasoline city [km/l]	15.3	-	12.2	-	11.1	-	10.9	-
Gasoline highway [km/l]	15.7	-	14.1	-	12.7	-	13.1	-
Equivalent city [km/le]	-	52.7	-	37.8	-	38.0	-	35.3
Equiv. highway [km/le]	-	39.6	-	30.8	-	35.1	-	29.0
Maintenance [R$]	3,269	1,739	4,363	6,322	5,268	6,322	-	-
Battery capacity [kWh]	-	26.8	-	50.0	-	50.0	-	66.5
Battery price [R$]	-	18,365	-	34,263	-	34,263	-	45,570

Table 5 - Best-selling ICVs [81]

Level	Entry	Compact	Medium	Luxury
Vehicle	Fiat Mobi	Volkswagen T-Cross	Jeep Compass	Jeep Commander
MSRP [R$]	75,000	150,000	230,000	276,000
Ethanol city [km/l]	9.6	8.2	7.2	7.0
Ethanol highway [km/l]	10.4	10.1	8.7	8.2
Gasoline city [km/l]	13.5	11.8	10.1	10.0
Gasoline highway [km/l]	15.0	14.3	12.0	11.4
Maintenance [R$]	3,940	4,394	5,006	5,006

Table 6 - Best-selling HEVs [65]

Level	Compact	Medium	Luxury
Vehicle	Chery Tiggo 5	Toyota Corolla Cross	Toyota RAV 4
MSRP [R$]	145,000	207,000	350,000
Ethanol city [km/l]	7.7	12.2	-
Ethanol highway [km/l]	8.3	9.9	-
Gasoline city [km/l]	10.7	17.8	17.1
Gasoline highway [km/l]	11.6	14.7	14.5
Maintenance [R$]	4,601	4,364	5,136

Table 7 - Best-selling PHEVs [65]

Level	Medium	Luxury
Vehicle	BYD Song	GWM Haval H6
MSRP [R$]	230,000	280,000
Gasoline city [km/l]	15.1	11.7
Gasoline highway [km/l]	13.2	10.4

Equivalent city [km/le]	35.6	28.7
Equivalent highway [km/le]	27.2	25.3
Maintenance [R$]	6,310	4,560
Battery capacity[kWh]	8.3	34.0
Battery price [R$]	5,687	23,299

Table 8 - Best-selling BEVs [65]

Level	Entry	Compact	Medium	Luxury
Vehicle	Renault E-Kwid	BYD Dolphin	BYD Yuan	Volvo XC40
MSRP [R$]	140,000	150,000	230,000	343,000
Equivalent city [km/le]	52.7	51.9	39.8	42.8
Equivalent highway [km/le]	39.6	43.5	33.1	36.0
Maintenance [R$]	1,749	3,280	3,280	2,487
Battery capacity [kWh]	26.8	44.9	60.5	69.0
Battery price [R$]	18,365	30,768	41,445	47,283

In summary the vehicles in Table 4, comparable pairs, are from same manufacture, same model, same category, same characteristics and therefore the main difference between them is the propulsion system. This makes it is possible to better analyze the TCO, knowing that the propulsion system is what manly impacts the TCO. However, the lack of availability of these models, only offered as ICVs and BEVs could limit this research. In order to address this issue, authors have, in Tables 5-8, presented best-selling vehicles that (i) better represent real automotive market in Brazil and (ii) are available in more varied propulsion systems. In short, this means that in the comparable pairs set of vehicles, the models are compared in a more objective way, though, the Brazilian market is not well represented. In the best-selling set, contrarily, vehicles have many different characteristics which makes comparison less objective, however, the benefit to this approach is that it better represents real world market.

General parameters

General parameters include lifetime [years], kilometers travelled [km/year], discount rate [%], national consumer price index [%], rate of change in battery price [%], and home charger [R$]. Table 9 lists the description, variable, and value adopted for these parameters.

Table 9 - General parameters

Description	Variable	Value
Lifetime [years]	N	10
Km travelled [km/year]	VKT	13,059
Discount rate [%]	r_d	7.71
National consumer price index [%]	$IPCA$	5.97
Rate of change in battery price [%]	r_b	11
Home charger [R$]	HC	7,500

Lifetime (N) refers to the period of vehicle's ownership. Usually, consumers take the decision of replacing a vehicle based on factors, such as warranty and financing time. Most manufacturers offer 3 to 5 years of warranty for vehicles and 8 years for batteries. In relation to financing time, the maximum term permitted by banks is 5 years, ANEF (2023). This research assumes 10 years for lifetime, considering the average age of 10.9 years for passenger vehicle fleet in Brazil [84] – some other authors also use this value, for example, [23].

Kilometers travelled (VKT) corresponds to distance driven during a year. Each region of the country has its own average due to particular characteristics and diversity of consumer behavior. [85] estimates the average of 13,059 km/year, contemplating all states in Brazil. Thus, the value of 13,059 km/year is applied in the case studies - other authors use similar values, for example, [78]. VKT = 60,000 km/year illustrates the high-distance usage in order to represent consumers that use the vehicle for taxis or mobility apps [86]. VKT = 5,000 km/year is used to exemplify a very low-distance usage for consumers that do remote work, for example, has become more common since the COVID-19 pandemic [87].

The annual discount rate (r_d) is employed to calculate the NPV of future cash flows. For this study, the average of the main rates used in Brazil is calculated from historical data of 2010 to 2023. National Consumer Price Index (IPCA) = 5.97%, General Market Price Index (IGP-M) = 7.72%, and Special System for Settlement and Custody (SELIC) = 9.44% are considered and the overall average of 7.71% is adopted [88].

For battery, cheaper minerals, such as lithium, nickel, and cobalt have been important drivers for price decline over past few years. According to [82], from 2013 to 2023 prices have fallen an average of 15% each year. [89] expects the price to fall by an average of 11% per year from 2023 to 2030. Therefore, this estimated value is adopted as rate of change in battery price (r_b).

Home chargers (HC) can minimize recharging time compared to conventional outlet, mainly because of the higher power availability. Most models sold in the country promise to charge batteries of BEVs and PHEVs in less than half the time of charging at a conventional outlet. The price of this equipment can vary from R$ 3,000 to R$ 12,000 proximally [90]. Thus, the average price of R$ 7,500 is employed in this analysis.

Therefore, data for general parameters were acquired from: manufactures that provided warranty periods, banks that offered financing times, specialized company that presented fleet figures, reliable companies in automotive sector that ran statistics, government agencies that have historical indexes, and papers with similar scope.

<u>Parameters by propulsion system</u>

Some parameters used for TCO calculations are specific to propulsion systems. Insurance rate [%], maintenance rate [%], and depreciation [%] are examples. Table 10 shows the description, variable, and value of these parameters for each propulsion system analyzed.

Table 10 - Parameters by propulsion system

Description	Variable	ICV	HEV	PHEV	BEV
Insurance rate [%]	ri	4.5	3.4	3.4	3.7
Maintenance rate [%]	rm	0.6	0.4	0.4	0.2
Depreciation rate [%]	φ	$n = 1 \rightarrow 10\%$ $n = 2\ldots10 \rightarrow 5\%$	$n = 1 \rightarrow 15\%$ $n = 2\ldots10 \rightarrow 10\%$		

Car Insurance Price Index [91] estimates the insurance rate (ri) in relation to the vehicle's market value. For February/2024, on average, this variable corresponds to 4.5% for ICVs, 3.4% for HEVs and PHEVs, and 3.7% for BEVs. Therefore, these are the percentages assumed for this research.

Most manufactures recommend maintenance every 10.000 km or 12 months. The maintenance costs for the first 5 years are announced on the manufacture's website. For this study, the average value of the total maintenance is calculated. Then, the percentage in relation to MSRP is computed and the average for each propulsion system is adopted. Thus, the maintenance rate (rm) for ICVs, HEVs, PHEVs, and BEVs corresponds to 0.6%, 0.4%, 0.4%, and 0.2%; respectively.

Regarding to vehicle's depreciation rate (φ), this study uses 10% in the first year and 5% in the following years for ICVs. In relation to EVs, the depreciation rate employed is of 15% in the first year and 10% in the following years. These values are similar to those found in previous researches, such as in [92] that applies 10.4% for ICVs and 13.9% for EVs, [29] that assumes 7-12% depending on powertrain, and [68] that adopts 15% for ICVs and 17-21% for EVs.

Most Brazilian consumers use Fipe Table in order to know the value of a used car and then, calculate its depreciation rate. It is known that Fipe Table may not reflect the actual real world final price of a vehicle, since factors such as negotiation, region, condition, color, accessories, supply, and demand for a specific automobile can vary. However, it is still used as a reference by dealers and final consumers [93].

For ICVs, as an example, considering the best-selling compact vehicle used in this study, T-Cross, the 2024 model is worth R$ 106,835 in March of 2025 while a brand-new model is R$ 119,990 in the manufacture's website [93]. This is about 11% depreciation in the first year. Additionally, according to by [94] the average depreciation for small vehicles in the first year is 10%.

For EVs, the market in Brazil is very incipient. Therefore, there is no reliable data base for depreciation, especially because of the lack of EV models and the year it was introduced in the market. The number one best-selling BEV in Brazil taking in consideration the entire year of 2024, for example, was BYD Dolphin Mini which began selling in the country in February of 2024. There is still not enough market history for calculating overall depreciation rates. However, considering the best-selling compact vehicle, used in this study, BYD Dolphin, it is worth R$ 127,867 in March of 2025 while a brand-new vehicle is advertised in manufacture's website for R$ 149,800 [93]. This represents about 15% depreciation in the first year.

According to [62], depreciation for EVs tends to be faster than for ICVs. This can be seen by the examples of best-selling compact ICV (T-Cross) and BEV (Dolphin) used in this study. Moreover, the first year is the one with the most significant depreciation over the vehicle's market value [85]. Thus, the values used in this research of 10% depreciation in the first year and 5% in the following years for ICVs and 15% in the first year and 10% in the following years for BEVs are in accordance with recent international published papers, Brazil's Fipe Table, and agencies of the sector.

As can be observed, data for propulsion systems was obtained from: industry index for insurance, manufactures website for maintenance schedules, and mainly economic research foundation for depreciation.

Parameters related to discounts, subsidies, and monetary incentives

Discounts, subsidies, and monetary incentives can be offered at one-time (initial type) or recurrent time (annual type). These include: retailer's discount [R$], purchase subsides [R$], monetary incentives [R$], as well as annual subsidies for vehicle [R$] and electricity [R$]; as Table 11.

Table 11 - Parameters related to discounts, subsidies, and monetary incentives

Type	Description	Variable	Value
Initial	Retailer's discount [R$]	RD	-
	Subsidies for vehicle purchase [R$]	SV	-
	Monetary incentives for home charger [R$]	$MIHC$	BEV-C and BEV-M = R$ 7,500
Annual	Subsidies for vehicle [R$]	ASV	BEV-C and BEV-M = R$ 3,280
	Subsidies for electricity [R$]	ASE	91.6% (n = 1) … 72.0% (N = 10)

Regarding the retailer's discount (RD), for the chosen vehicles there are no reduction announced on manufacture's website. Therefore, this variable is set as zero in Table 11.

In relation to the purchase subsides, as mentioned in the Section 2, tax exemption for EV imports is being resumption. Specifically for consumers, there are no subsidies for vehicle purchase (SV) as shown in the Table 11.

A few manufactures have monetary incentives for consumers related to home charger. BYD, for example, offer the equipment for free with the purchase of the following vehicles: Dolphin or Yuan. Since home chargers cost on average R$ 7,500 this value is employed as monetary incentive ($MIHC$).

In relation to annual subsides for vehicle, some manufactures include free maintenance for the first years of ownership. BYD offers free maintenance for the BEVs. Thus, the sum of the first 5 scheduled maintenances, R$ 3,280, is applied as annual subsidy (ASV) for Dolphin and Yuan [95].

Concerning annual subsides for electricity (ASE), if the vehicle owner has solar photovoltaic systems at home, the net-metering policy in force by the Law 14.300/2022 is applied. In this case, a percentage discount (NM) can reduce the energy cost related to home charging of BEVs and PHEVs. There is a transition rule from REN 482/2012 to Law 14.300/2022, which determines that the compensation depends on the date the consumer joins the net-metering system [96].

- <u>before 2023</u>: all electricity tariffs are compensated until 2045, that means NM = 100%.
- <u>from 2023 to 2028</u>: there is a gradual payment of the Line B (around 28% of the tariff), which corresponds approximately to NM = 95.8% in 2023, NM = 91.6% in 2024, NM = 87.4% in 2025, NM = 83.2% in 2026, NM = 79.0% in 2027, NM = 74.8% in 2028, and NM=72.0% in 2029.
- <u>after 2029</u>: compensation will be defined by ANEEL based on the benefits of distributed generation. In this case, NM = 72.0% is adopted, considering that the consumer will pay for Line B entirely and the government will subside all the other components of the tariff.

This research assumes 2024 as the base year. Therefore, NM employed goes from 91.6% to 72.0%.

As shown, parameters regarding discounts, subsides, and incentives were found in manufacture's websites since that is how brands publish offers and country's laws as governments have official electricity regulations.

<u>Parameters related to energy costs</u>

Parameters related to energy costs (fuel and electricity) include: the price of ethanol [R$/l], gasoline [R$/l], electricity at home [R$/kWh], electricity at public places [R$/kWh], and rates of change in fuel and electricity prices [%]. Table 12 shows the description, variable, and values adopted in this research.

Table 12 - Parameters related to energy costs

Description	Variable	Value
Ethanol price [R$/l]	$EthanPrice$	3.42
Gasoline price [R$/l]	$GasolPrice$	5.61
Electricity home price [R$/kWh]	$HElecPrice$	0.70
Electricity public price [R$/kWh]	$PElecPrice$	2.00
Rate of change in fuel prices [%]	r_f	7.78
Rate of change in electricity prices [%]	r_e	6.21

Ethanol and gasoline prices are published by Brazilian National Agency for Petroleum, Natural Gas and Biofuels [97]. For Abril/2024, in Sao Paulo state, these data are R$ 3.42 and R$ 5.61, respectively.

In relation to electricity price for home charge, considering residential consumer and CPFL Paulista company; the effective cost of energy tariff employed is 0,70 R$/kWh [98]. For the price of electricity in public charge stations, based on market observation published by [99], an average of 2.00 R$/kWh is assumed.

For annual rate of change in fuel price (r_f), the average increase of gasoline and ethanol is calculated from historical data of the last 10 years, obtaining 7.78% [97]. The annual rate of change in electricity price (r_e) considered is 6.21%, as the average readjustment of the last 5 years extracted from [100].

As demonstrated, all parameters regarding energy costs were obtained from Brazilian National Agency, Brazil's Electric Power Regulator, car industry leaders, and non-state-owned group of electric energy.

Parameters related to taxes and fees

The acquisition of a vehicle includes taxes and fees that can be divided in initial costs (registration and plate [R$]) and annual costs (ownership tax [R$], license [R$], and mandatory insurance [R$]). Table 13 presents the type, description, variable, and value related to initial and annual taxes and fees parameters.

Table 13 - Parameters related to taxes and fees

Type	Description	Variable	Value
Initial taxes and fees	Registration and plate [R$]	TF	432.49
Annual taxes and fees	Ownership tax [%]	$IPVA$	ICV=4% EV=2%
	License [R$]	$CRLV$	160.22
	Mandatory insurance [R$]	$DPVAT$	-

The values adopted for parameters related to taxes and fees refer to the Sao Paulo state in 2024. Hence, regarding initial taxes and fees for registration and plate (TF), the price charged corresponds to R$ 432.49 for all passenger vehicles. In regards to annual taxes and fees, Motor Vehicle Ownership Tax ($IPVA$) tax is 4% for ICVs and there is a benefit for EV owners decreasing the value to 2% on vehicle's market value. In relation to annual licensing ($CRLV$), the price is R$ 160.22 for all passenger vehicles. Lastly, mandatory insurance ($DPVAT$) has not been charged since 2021, therefore its value is zero in this study [77].

As can be noted all parameters related to taxes and fees were obtained from the State of Sao Paulo government official website. It is important to highlight that others states may have different rules and prices. However, Sao Paulo is the number one state when it comes to EV participation in the market [17].

Parameters related to consumer behavior

Some factors related to consumer behavior influence TCO of the vehicles. These factors include: electricity charged at home [%], electricity usage [%], consumption adjustment [%], city trip [%], and gasoline usage [%]; listed in Table 14.

Table 14 - Parameters related to consumer behavior

Description	Variable	Value
Electricity charged at home [%]	$\alpha_{i,n}$	85
Electricity usage [%]	$\beta_{i,n}$	PHEV-M=1.88 PHEV-L=9.25
Consumption adjustment [%]	$\gamma_{i,n}$	100
City trip [%]	$\theta_{i,n}$	54
Gasoline usage [%]	$\mu_{i,n}$	70

PHEVs and BEVs can be charged at home ($\alpha_{i,n}$) or public stations. In [26], the percentage of electricity charged at home is 90%. According to [101], more than 80% of the members from Brazilian association of EV owners recharge at home. Thus, this paper adopts an average value between these references, assuming 85% of recharge at home for PHEVs and BEVs.

The electricity usage ($\beta_{i,n}$) refers to the percentage of recharges done by PHEV owners. A study of the International Council on Clean Transportation (ICCT) shows that most owners do not use the batteries as estimated by regulatory agencies. The number of kilometers driven with electric motors is 26% to 56% (average 41%) lower than the value published by Environmental Protection Agency [102]. For the PHEVs analyzed in this study, from the total range (electric + combustion), the electricity usage parameter was calculated, considering 59% of the electric range. Therefore, 1.88% and 9.25% are employed for PHEV-M and PHEV-L, respectively.

Consumption adjustment ($\gamma_{i,n}$) is employed since the battery on EVs can have decreased efficiency due to factors as extreme weather. [30] assume for BEVs a 30% decrease in energy efficiency when driving at very high or very low temperatures. However, in Brazil, the official consumption data published in [45] PBEV (2024) already applies a correction factor. This decreases the information by 30% in relation to international standards as Worldwide Harmonized Light Vehicle Test Procedure (WLTP), Environmental Protection Agency (EPA), and New European Driving Cycle (NEDC). According to [103], the application of this correction factor is done in order to better represent the real-life value. Therefore, for Brazilian case study, consumption adjustment should not impact TCO calculation.

Percentage of city ($\theta_{i,n}$) and highway trip also effects the consumption of vehicles. The highest consumption levels for EVs are related to driving highway/interstates and with highspeed, while for ICVs it is the opposite [104]. Currently, there are three main consumption testing standards used by automakers; each test assumes its city and highway percentages. The NEDC applies 66% for city and 34% for highway; WLTP employ 52% for city and 48% for highway; EPA uses 45% city and 55% for highway. The average value of 54% for city trip, from these references, is applied in this study. Other authors, such as [30], assume similar value of 50% for city trip.

In Brazil, consumers have the choice of using a flex-fuel vehicle with gasoline and/or ethanol. The expansion of biofuel production reflects the search for more sustainable energy sources and efforts to reduce dependence on fossil fuels and mitigate environmental impacts. Consumers usually choose between gasoline and ethanol based on the price ratio rule. If below 70%, consumers commonly opt for ethanol over gasoline. According to The International Council on Clean Transportation (ICCT, 2024a), in 2020 one-third of the fuel demand from the national passenger car fleet was supplied by hydrous ethanol. Besides, according to this reference, over the past few years, ethanol consumption has stagnated while gasoline sales increased. Therefore, the parameter for gasoline usage ($\mu_{i,n}$) considered is 70% (μ = 100% would represent the absence of ethanol, for countries where that is not a possibility and μ = 0% would signify the use of only ethanol).

The previous paragraphs show that data related to consumer behavior were taken from industry association, international council, international standards, and other referenced authors. Thus, it was demonstrated through Section 4, that all the sources of the data are reliably, and therefore, quality information is provided.

Scenarios

Sensitivity analysis is related to uncertainties in input variables or parameters of a model used for decision making. In order to study the sensitivity of the TCO model, variables or parameters that significantly influence the results are chosen so that the effect of the changes on the results can be observed.

Several authors performed sensitivity analysis for TCO. [71] implements a sensibility analysis on maintenance and repair cost, average annual driving distance, volatility of fuel price, and level of purchase subsidies for EVs. [68] presents the assessment of the effect of changing in the depreciation rate, taxes, and fuel prices on the TCO. [30] studies sensitivity for annual kilometers travelled, home charging availability, and percentage of urban travel. [24] conducts sensitivity analysis for purchase incentives, temperature adjustment factor, expanded TCO, alternative transportation costs, annual vehicle miles travelled, discount rate, battery replacement, and gasoline and electricity price growth. [28] implements a sensitivity analysis by adding 10% to each parameter related to price (gasoline, electricity, MSRP, subsides, public transportation price, and discount rate), technology (energy consumption and range anxiety) and travel pattern (daily vehicle kilometers travelled). [26] tests variations of interest rate, lifetime, and annual milage. [23] executes a sensitivity analysis with kilometers travelled per year, duration of vehicle ownership, energy costs, vehicle initial value, vehicle final value, and financial incentives value. [31] evaluates different discount rates and variations of electricity prices in relation to the oil price. [29] studies government subside or retailers discount, and battery price reduction. [74] presents a sensitivity analysis for low, mid, and high usage of the vehicle (annual driving distance).

In this paper, different scenarios are created in order to analyze how possible changes, based on the particular characteristics, could encourage or discourage EV adoption by increasing or decreasing TCO, thus altering the path to energy transition. The scenarios that are described and used are not intended to represent precise predictions of the future, but rather provide means to evaluate the impacts that different behaviors, subsidies, regulations, and policies cause on TCO.

Table 15 presents twenty-three scenarios grouped into seven case studies. Scenario 0 is the baseline, represented by the comparable vehicles listed in Table 4, considering the parameters set as the previous section. In scenarios 1-8 behavior parameters are changed, assuming the lowest and highest possible values for each one (0% and 100%). From scenarios 9-11, it is possible to evaluate TCO without government subsidies for energy and vehicles. Extreme positive and negative situations for EVs are analyzed in scenarios 12-14 and 15-17, respectively; contemplating the minimum, average, and maximum adopted VKT. In scenarios 18-21, the impact of different discount rates (5%, 10%, 15%, and 20%) is evaluated, as [72]. Finally, Scenario 22 shows the TCO values for best-selling vehicles in Brazil listed in tables 5-8.

Table 15 - Scenarios for studying TCO

Scenario	Case Study	Parameter	Value
0	Baseline or base/reference scenario - comparable vehicles (listed in Table 4)		
1	Changing behavior parameters	Home charge (α)	0%
2			100%
3		City trip (θ)	0%
4			100%
5		Gasoline usage (μ)	0%
6			100%
7		VKT	5,000 km/year
8			60,000 km/year
9	Excluding government subsidies	ASE	0
10		$IPVA$ (EVs)	4%
11		ASE and $IPVA$ (EVs)	0 and 4%
12	Extreme positive scenario for EVs (ASE = 1, NM = 91.6%-72.0%, α = 100%, θ = 100%, μ = 100%, $IPVA$ = 2%)	VKT	13,059 km/year
13			5,000 km/year
14			60,000 km/year
15	Extreme negative scenario for EVs (ASE = 0, NM = 0%, α = 0%, θ = 0%, μ = 0%, $IPVA$ = 4%)	VKT	13,059 km/year
16			5,000 km/year
17			60,000 km/year
18	Changing discount rates	Discount rate (r_d)	5%
19			10%
20			15%
21			20%
22	Best-selling vehicles in Brazil (listed in Tables 5-8)		

5. Results and Discussion

The results and discussion are organized in five sub-sections. The first one, Sub-section 5.1, refers to the TCO results from comparable ICVs and BEVs available in Brazil. The objective is to directly compare the TCO of vehicles with combustion or electric technologies in a fair way, that means, from the same model and manufacture varying powertrain. The second sub-section, 5.2, corresponds to the TCO results for the thirteen best-selling ICVs, HEVs, PHEVs, and BEVs in Brazil. This sub-section aims to evaluate the TCO for preferred vehicles by most consumers, considering similar vehicles in terms of size, features, and price. Sub-section 5.3 shows the

TCO indicator across comparable and best-selling groups of vehicles for ICVs and BEVs. Sub-section 5.4 introduces the green premium concept and the value of this variable for the most relevant scenarios. Lastly, Sub-section 5.5 presents a discussion including non-cost related factors, other countries experience, and police recommendations.

5.1 Comparable ICVs and BEVs available in Brazil

The set of comparable ICVs and BEVs is composed by four pairs of vehicles - one for each level: entry, compact, medium, and luxury. The vehicles that comprise this set are Renault Kwid, Peugeot 208, Peugeot 2008, and BMW X1; as Table 16.

Table 16 - Comparable ICVs and BEVs available in Brazil

Level	Propulsion System	Manufacture and Model
Entry	ICV	Renault Kwid
	BEV	Renault Kwid e-Tech
Compact	ICV	Peugeot 208
	BEV	Peugeot e-208
Medium	ICV	Peugeot 2008
	BEV	Peugeot e-2008
Luxury	ICV	BMW X1
	BEV	BMW iX1

For the vehicles listed in Table 16, Table 17 presents the EC, AC, and TCO values in thousand R$. These values refer to the base scenario. Energy and annual costs (EC and AC) of all vehicles are higher for ICVs than for BEVs, as expected. Regarding the Total Cost of Ownership (TCO), BEVs are more expensive than ICVs for entry and compact levels, while the opposite occurs for medium and luxury levels; as justified in the sequence.

Table 17 - EC, AC, and TCO values [thousand R$] for base scenario (Scenario-0)

Variable [thousand R$]	Entry		Compact		Medium		Luxury	
	ICV	BEV	ICV	BEV	ICV	BEV	ICV	BEV
EC	52	10	62	15	69	13	68	14
AC	96	55	114	91	147	71	241	129
TCO	151	182	180	300	246	223	460	443

In order to explain the TCO differences between the first two and last two levels in Table 17, Figure 1 shows the costs by phase of each vehicle for the base scenario. The phases of acquisition (IC), operation (AC), and disposal (RV) make up the TCO. As can be observed, for entry and compact levels the BEV acquisition cost is almost two/three times the ICV acquisition cost (in green on the graph). However, for medium and luxury levels these costs are closer, around 20-30% higher for BEVs. Therefore, the combination of reasonable acquisition costs (in green on the graph) and low annual costs (in blue on the graph) for BEVs of medium and luxury levels justify their lower TCO in relation to the corresponding ICVs.

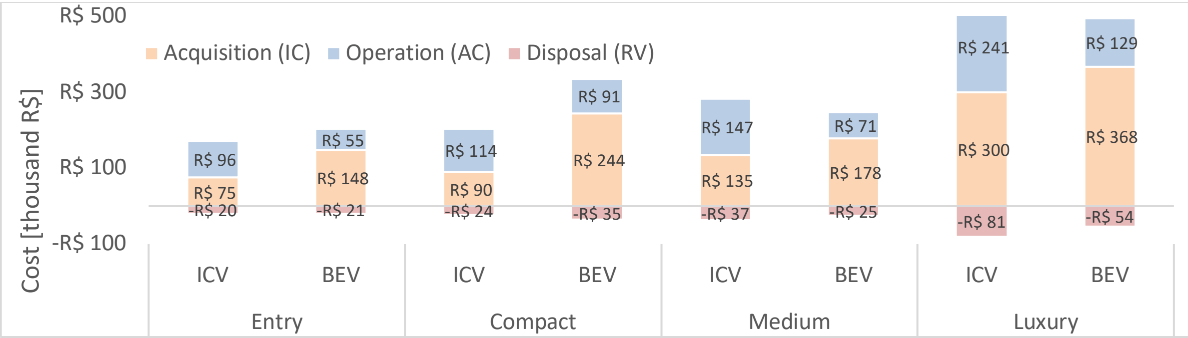


Figure 1 - Cost by phase for base scenario

Figure 2 illustrates the TCO by component for the base scenario, making it possible to identify the percentage of the TCO spent on depreciation, energy, insurance, maintenance, battery, and taxes. According to this figure, for vehicles in Table 16, BEVs depreciate around 70%; while ICVs 40%. As seen previously, energy costs (fuel or electricity) are higher for ICVs than for BEVs, approximately 30% and 5%, respectively. The percentage of the TCO spent on insurance and maintenance do not change significatively between the two propulsion systems, being the first around 14% and the second 3%; although the costs of these variables for ICVs are higher than for BEVs, as parameters in Table 10. Battery costs for BEVs represent 2-3% of the TCO. Taxes are higher for ICVs (14%) than for BEVs (8%) due to government incentives for electric mobility.

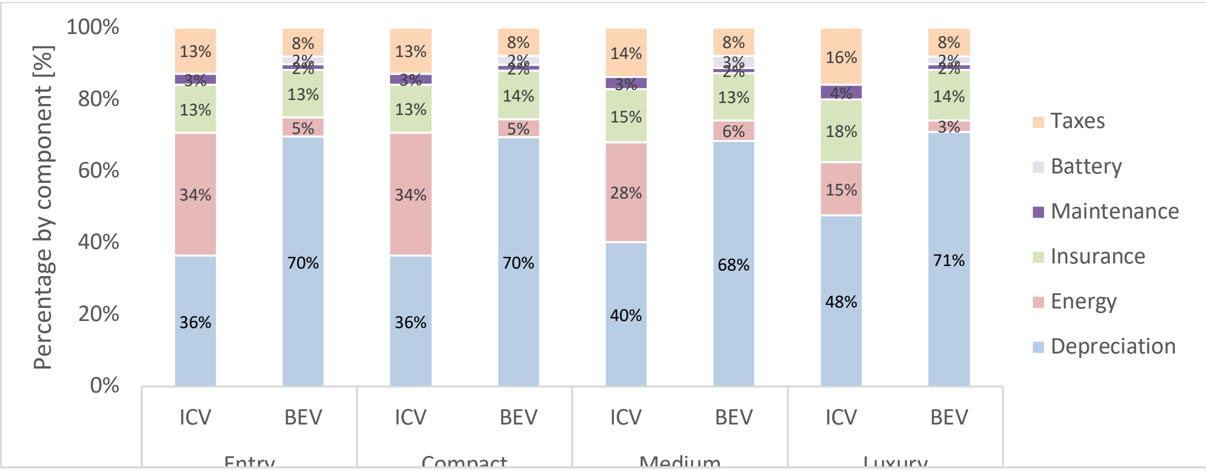
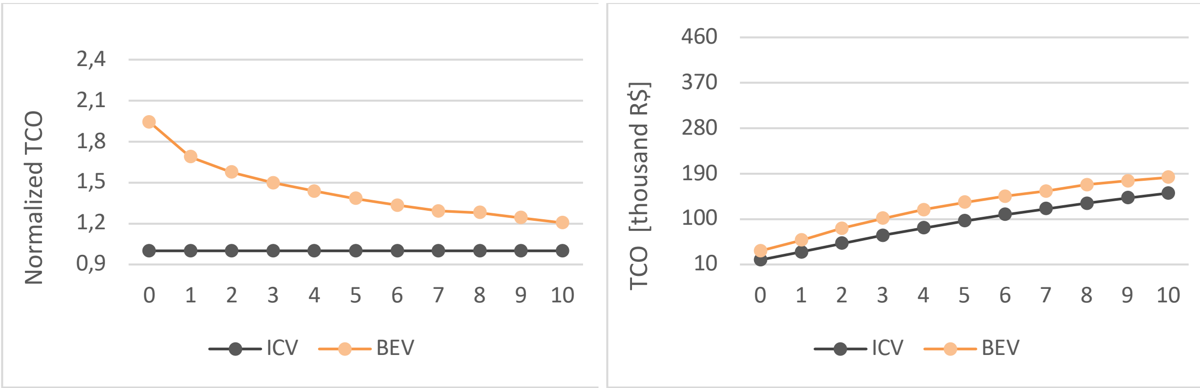
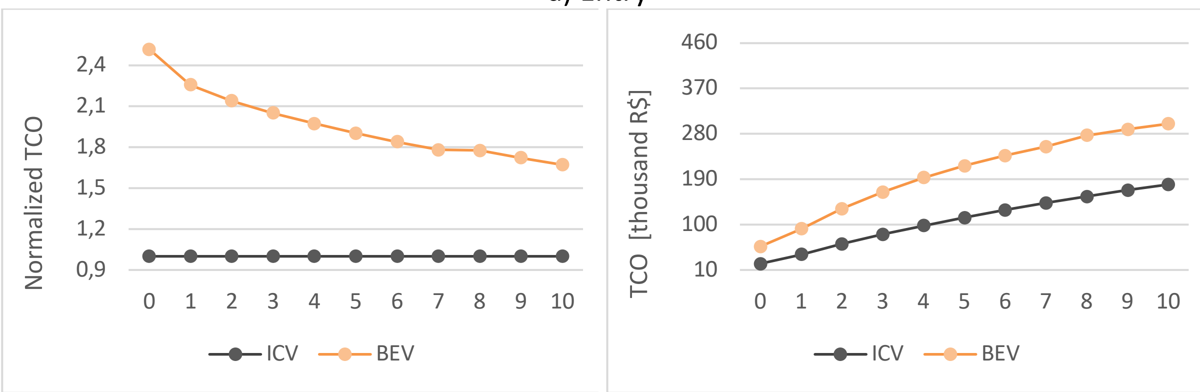


Figure 2 - TCO by component for base scenario

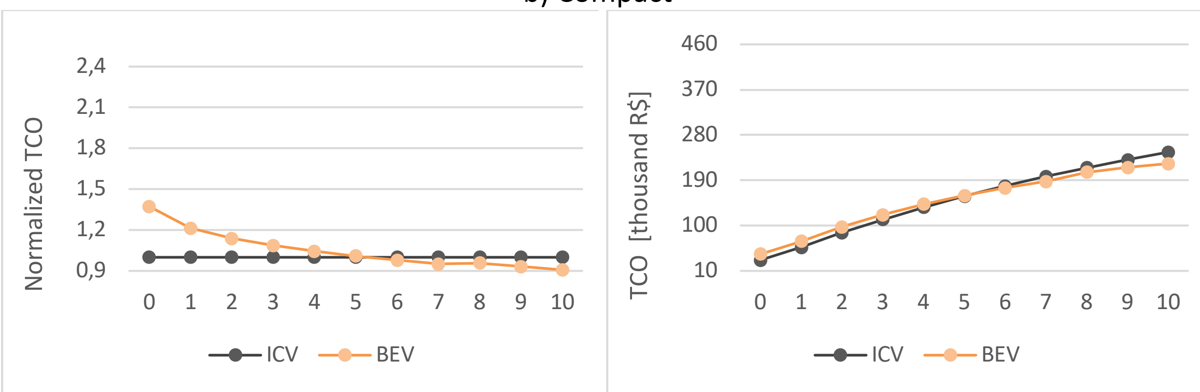
Finally, to conclude the base scenario, Figure 3 shows TCO (normalized and annual values) of ICVs and BEVs throughout ten years. From this figure, it is possible to evaluate when ICVs and BEVs in Table 16 will have cost parity. For entry and compact levels, ICVs and BEVs will not have cost parity in the period analyzed in this study. ICVs and BEVs from medium and luxury levels reach cost parity approximately in the fifth and sixth years, respectively. The reason again is that reasonable acquisition costs and low annual costs make EVs cost-competitive in relation to ICVs. After 10 years, the lowest final TCO is R$ 151,375.72 for ICV and R$ 182,440.75 for BEV (entry level) and the highest is R$ 460,006.32 for ICV and R$ 442,809.04 for BEV (luxury level).



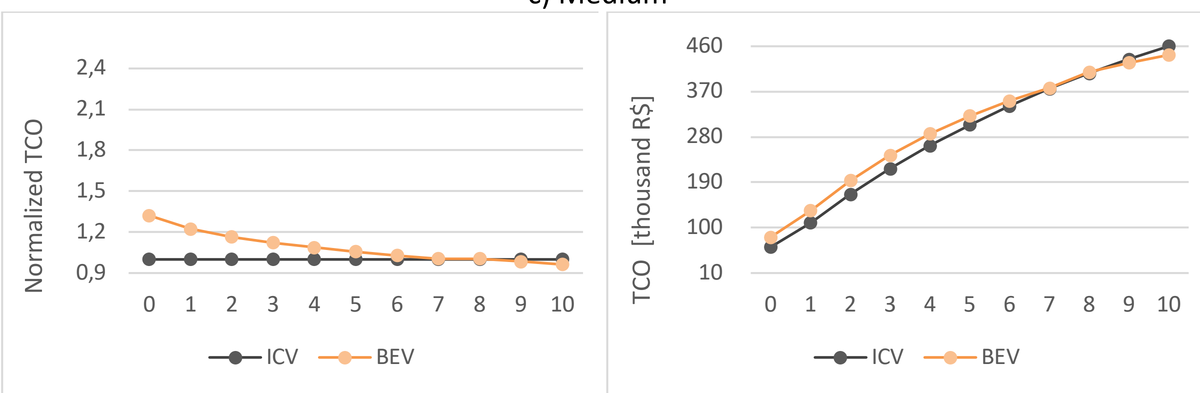
a) Entry



b) Compact



c) Medium



d) Luxury

Figure 3 – TCO (normalized and annual values) for base scenario

From this point, the base scenario is used as reference for three new analyzes. In the first one, the base scenario is compared to eight scenarios changing behavior parameters. In the second analysis, the reference scenario is compared to three scenarios that exclude government subsidies. In the third, the base scenario is compared to six extreme positive and negative scenarios for EVs.

Table 18 displays results from eight scenarios in which four behavior parameters are changed: home charge (α), city trip (θ), gasoline usage (μ), and VKT. All of them assume the lowest and highest possible or considered value, for example: 0% - 100% and 5,000 km/year - 60,000 km/year. This table shows the EC, AC, and TCO variation [%] of these new eight scenarios in relation to base scenario presented in Table 17. The average values by propulsion system for entry, compact, medium, and luxury levels are considered. Home charge (α) parameter does not affect ICVs, as well as gasoline usage (μ) parameter does not impact BEVs. For this reason, they are equal to zero in the table. The next four paragraphs describe the results in Table 18 for each behavior parameter, associating them with their reference values in tables 9 and 14.

In the reference scenario home charger for BEVs, α parameter, is equal to 85% (Table 14). For α = 0% (Scenario-1), that is, considering that there is no charger at home or it is not used for any reason; EC, AC, and TCO of BEVs increase 360.09%, 56.55%, and 17.26%, respectively. In an opposite scenario, α = 100% (Scenario-2), these values decrease 63.54%, 9.98%, and 3.05%, respectively. As can be observed, the increase in the variation for Scenario-1 is more significative than its reduction for Scenario-2. The reason is that in reference scenario, the home charger parameter, α, is equal to 85%; far from 0% adopted in Scenario-1 and close to 100% considered in Scenario-2.

The percentage of city trip, θ parameter, is equal to 54% in the reference scenario (Table 14). For θ = 0% (Scenario-3), i.e., for situations in which the vehicle only drives on the highway; EC, AC, and TCO of ICVs reduce 6.58%, 2.78%, and 1.65%, respectively; while for BEVs rise 10.39%, 1.61%, and 0.49%, respectively. In a contrary situation, θ = 100% (Scenario-4), these values for ICVs increase 5.61%, 2.37%, and 1.41%, respectively; while for BEVs decrease 8.85%, 1.37%, and 0.42%, respectively. For both propulsion system, ICVs and BEVs, scenarios 3 and 4 present similar results with inverted sign for the three types of variation (EC, AC, and TCO). That happens because the city trip, θ parameter, in the reference scenario is around the middle (54%) of the lowest (0%) and highest (100%) values considered in these scenarios.

In the reference scenario the percentage of use gasoline for ICVs, μ parameter, is equal to 70% (Table 14). For μ = 0% (Scenario-5) use of only ethanol is considered. In this situation; EC, AC, and TCO of ICVs decrease 9.55%, 4.94%, and 3.08%, respectively. In a reverse scenario, μ = 100% (Scenario-6), these values increase 0.35%, 0.18%, and 0.12%, respectively. The justification for higher values in Scenario-5 than in Scenario-6 is the price of fuels employed in the studies. Ethanol price (3.42 R$/l) is more economically viable, since it represents 61% of the gasoline price (5.61 R$/l).

The annual vehicle kilometers travelled, VKT parameter, is equal to 13,059 km/year in the reference scenario (Table 9). Considering VKT = 5,000 km/year (Scenario-7), EC falls 61.71% for ICVs and BEVs; AC reduces 28.25% for ICVs and 9.69% for BEVs; and TCO decreases 17.19% for ICVs and 2.96% for BEVs. For VKT = 60,000 km/year (Scenario-8), EC grows 359.45% for ICVs and BEVs; AC rises 164.57% for ICVs and 56.45% for BEVs; and TCO increases 100.15% for ICVs and 17.23% for BEVs. As expected, higher VKT increases costs for both ICVs and EVs; while lower VKT decreases their costs. However, ICVs are more sensible for VKT variation. For example, AC variation in relation to base scenario for ICVs is around 3.0 times higher than for BEVs; this value considering TCO variation for ICVs is around 5.8 times higher than for BEVs.

Table 18 - EC, AC, and TCO variation [%] in relation to base scenario, changing behavior parameters (average by propulsion system for all levels)

Scenario			$\Delta\ EC$ [%]		$\Delta\ AC$ [%]		$\Delta\ TCO$ [%]	
			ICV	BEV	ICV	BEV	ICV	BEV
1	Home charge	α = 0%	0.00	360.09	0.00	56.55	0.00	17.26
2		α = 100%	0.00	-63.54	0.00	-9.98	0.00	-3.05
3	City trip	θ = 0%	-6.58	10.39	-2.78	1.61	-1.65	0.49
4		θ = 100%	5.61	-8.85	2.37	-1.37	1.41	-0.42
5	Gasoline usage	μ = 0%	-9.55	0.00	-4.94	0.00	-3.08	0.00
6		μ = 100%	0.35	0.00	0.18	0.00	0.12	0.00
7	VKT	5,000	-61.71	-61.71	-28.25	-9.69	-17.19	-2.96
8		60,000	359.45	359.45	164.57	56.45	100.15	17.23

Table 19 shows results from three scenarios in which government subsidies are excluded. This table shows the EC, AC, and TCO variation [%] of these three new scenarios in relation to base scenario presented in Table 17. Since only BEVs are impacted by government subsidies, their average values for entry, compact, medium, and luxury levels are considered. $IPVA$ parameter does not affect energy cost of BEVs. For this reason, it is equal to zero in the table. The next three paragraphs describe the results in Table 19 for each change in government subsidy, associating them with their reference values in tables 11 and 13.

The annual subsidy for electricity is represented by ASE and NM parameters. In the reference scenario these parameters are set to 1 (on) and 91.6%-72%, respectively (Table 11). According to Table 19, for ASE = 0 (off) in Scenario-9, that means, without any electricity subsidy; EC, AC, and TCO of BEVs increase 105.89%, 16.63%, and 5.08%, respectively.

In the reference scenario the motor vehicle ownership tax, $IPVA$ parameter, is equal to 2% for BEVs (Table 13). For $IPVA$ = 4% (Scenario-10) this subsidy is excluded, doubling the tax amount to 4%, as for ICVs. In this situation, AC and TCO of BEVs rise 24.07% and 7.30%, respectively.

Finally, the simultaneous exclusion of the two previously mentioned government subsidies, ASE = 0 and $IPVA$ = 4% (Scenario-11) also impact BEV costs. In this case EC, AC, and TCO grow 105,89%, 40.69%, and 12.37%, respectively. Therefore, this scenario increases the AC and TCO variation in relation to base scenario 2.4 times more than the individual exclusion of ASE (Scenario-9) and 1.7 times more considering the individual exclusion of $IPVA$ (Scenario-10).

Table 19 - EC, AC, and TCO variation [%] in relation to base scenario, excluding government subsidies (average of BEVs for all levels)

Scenario		$\Delta\ EC$ [%]	$\Delta\ AC$ [%]	$\Delta\ TCO$ [%]
9	ASE = 0	105.89	16.63	5.08
10	$IPVA$ = 4%	0.00	24.07	7.30
11	ASE = 0 + $IPVA$ = 4%	105.89	40.69	12.37

Table 20 displays results from six scenarios in which extreme situations for EVs are considered. For each extreme scenario (positive and negative) VKT assumes regular (13,059 km/year), minimum (5,000 km/year), and maximum (60,000 km/year) values adopted in this study. An extreme positive scenario for EVs is defined as ASE = 1, NM = 91.6%-72.0%, α = 100%, θ = 100%, μ = 100%, $IPVA$ = 2% for BEVs, and $IPVA$ = 4% for ICVs. An extreme negative scenario for EVs is set as ASE = 0, NM = 0%, α = 0%, θ = 0%, μ = 0%, and $IPVA$ = 4% for ICVs and BEVs. Table 20 shows the EC, AC, and TCO variation [%] of these six new scenarios in relation to base scenario presented in Table 17. In the reference scenario ASE = 1, NM = 91.6%-72.0%, α = 85%, θ = 54%, μ = 70%, $IPVA$ = 4% for ICVs, and $IPVA$ = 2% for BEVs (tables 11, 13, and 14). The average values by propulsion system for entry, compact, medium, and luxury levels are considered.

According to Table 20, the results of extreme positive scenarios for EVs (# 12, 13, and 14) vary depending on VKT value. As expected, for VKT = 13,059 km/year the costs (EC, AC, and TCO) of ICVs increase and of BEVs decrease. A VKT = 5,000 km/year reduces EC, AC, and TCO for both ICVs and BEVs; while a VKT = 60,000 km/year rises these values again for both. In this scenario, # 14, the impact of VKT variation is more significant for ICVs than for BEVs due to three reasons. First, there are no energy subsidies for ICVs; therefore ASE = 1, NM = 91.6%-72.0%, α = 100% do not impact ICVs. Second, θ = 100% (only driving in the city) and μ = 100% (only using gasoline) increase ICVs costs. Third, $IPVA$ in this scenario is the same as in the base scenario.

Still considering the extreme positive scenario for BEVs, two new analyses were performed. In the first analysis, the rate of change in battery price was altered from 11% (predicted by [89]) to 15% (average drop for the period 2013 to 2023). In this case, the TCO of BEVs reduced on average 0.80%. The second analysis considers that in the next years the depreciation of ICVs will be similar to that of BEVs since combustion propulsion systems may be considered outdated. For this case, the TCO of ICVs increased on average of 0.53%.

However, extreme negative scenarios for EVs (# 15, 16, and 17) benefit ICVs, since city trip (θ) and gasoline usage (μ) parameters are equal to 0% instead of 54% and 70%, respectively, as in the base scenario. For regular VKT (13,059 km/year) ICVs costs decrease and BEVs costs increase. Even for VKT = 5,000 km/year BEVs costs grow; while EC, AC, and TCO for ICVs fall. A VKT = 60,000 km/year rises EC, AC, and TCO for both, but mainly for BEVs because with α = 0% (only charging at home) the electricity cost goes from 0.70 R$/KWh to 2.00 R$/KWh.

Table 20 - EC, AC, and TCO variation [%] in relation to base scenario, considering extreme positive and negative scenarios for EVs (average by propulsion system for all levels)

Scenario			$\Delta\ EC$ [%]		$\Delta\ AC$ [%]		$\Delta\ TCO$ [%]	
			ICV	BEV	ICV	BEV	ICV	BEV
Positive scenario for EVs → ASE = 1, NM = 91.6%-72.0%, α = 100%, θ = 100%, μ = 100%, $IPVA$ = 2% for BEVs, and $IPVA$ = 4% for ICVs								
12	VKT [km/year]	13,059	5.93	-66.77	2.54	-10.48	1.52	-3.20
13		5,000	-59.44	-87.28	-27.28	-13.70	-16.61	-4.18
14		60,000	386.69	52.66	176.24	8.30	107.13	2.54
Negative scenario for EVs → ASE = 0, NM = 0%, α = 0%, θ = 0%, μ = 0%, $IPVA$ = 4% for ICVs and BEVs								
15	VKT [km/year]	13,059	-15.68	407.91	-7.48	88.04	-4.59	26.81
16		5,000	-67.72	94.47	-31.12	38.87	-18.95	11.81
17		60,000	287.39	2,233.62	130.19	374.43	79.05	114.18

Table 21 shows the TCO variation from base scenario presented in Table 17, for four scenarios in which discount rates are altered. The average value for each scenario is also displayed. The new discount rates (5%, 10%, 15%, and 20%) are justified by the lowest and highest economic index in Brazil from 2010 to 2023, as [88]. On average, the impact on TCO of changing the discount rate from 7.71% to 5% is 1.58%, to 10% is -1.33%, to 15% is -4.06%, and to 20% is -6.49%. As expected, the higher the discount rate the lower the TCO, since this variable is in the denominator of the Equation (1). The impact is more significant for ICVs than for BEVs due to their higher annual costs.

Table 21 - TCO variation [%] in relation to base scenario for different discount rates

Scenario			Entry		Compact		Medium		Luxury		Average
			ICV	BEV	ICV	BEV	ICV	BEV	ICV	BEV	
18	Discount rate (r_d)	5%	4.11	0.14	4.09	0.06	3.07	0.45	1.03	-0.30	1.58%
19		10%	-3.10	-0.28	-3.09	-0.23	-2.39	-0.50	-1.01	0.01	-1.33%
20		15%	-8.86	-1.19	-8.82	-1.06	-7.01	-1.75	-3.39	-0.41	-4.06%
21		20%	-13.47	-2.24	-13.42	-2.07	-10.85	-3.04	-5.72	-1.14	-6.49%

5.2 Best-selling ICVs, HEVs, PHEVs, and BEVs in Brazil

In this research the best-selling ICVs, HEVs, PHEVs, and BEVs are represented by thirteen vehicles. The vehicles are distributed among entry, compact, medium, and luxury levels; as Table 22.

Table 22 - Best-selling ICVs, HEVs, PHEVs, and BEVs in Brazil

Level	Propulsion System	Manufacture and Model
Entry	ICV	Fiat Mobi
	BEV	Renault Kwid e-Tech
Compact	ICV	Volkswagen T-Cross
	HEV	Chery Tiggo 5
	BEV	BYD Dolphin
Medium	ICV	Jeep Compass
	HEV	Toyota Corolla Cross
	PHEV	BYD Song
	BEV	BYD Yuan
Luxury	ICV	Jeep Commander
	HEV	Toyota RAV 4
	PHEV	GWM Haval H6
	BEV	Volvo XC40

For the vehicles listed in Table 22, Table 23 presents the EC, AC, and TCO values in thousand R$. Considering each level, in general, energy and annual costs (EC and AC) are high for ICVs, intermediate for HEVs and PHEVs, and low for BEVs. Regarding the total cost of ownership (TCO), BEVs are more expensive than vehicles that contain a combustion engine (ICVs, HEVs, and PHEVs) for entry and luxury levels; while the opposite occurs for compact and medium and levels; as justified in the sequence.

Table 23 - EC, AC, and TCO values [thousand R$] for base scenario

Variable [thousand R$]	Entry		Compact			Medium				Luxury			
	ICV	BEV	ICV	HEV	BEV	ICV	HEV	PHEV	BEV	ICV	HEV	PHEV	BEV
EC	57	10	65	66	10	76	59	52	13	79	51	68	12
AC	101	55	152	112	60	199	121	122	87	232	155	168	131
TCO	156	182	262	242	188	356	296	326	283	426	453	448	457

Figure 4 shows the costs by phase for each vehicle of Table 22. The phases of acquisition (IC), operation (AC), and disposal (RV) make up the TCO. As can be observed, for entry and luxury levels the BEV acquisition cost is almost two times the ICV acquisition cost (in green on the graph). However, for compact and medium levels ICVs, HEVs, PHEVs, and BEVs acquisition cost are similar, varying less than 16%. Therefore, the combination of reasonable acquisition costs (in green on the graph) and low annual costs (in blue on the graph) for BEVs of compact and medium levels justify their lower TCO in relation to the corresponding vehicles that contain a combustion engine (ICVs, HEVs, and PHEVs).

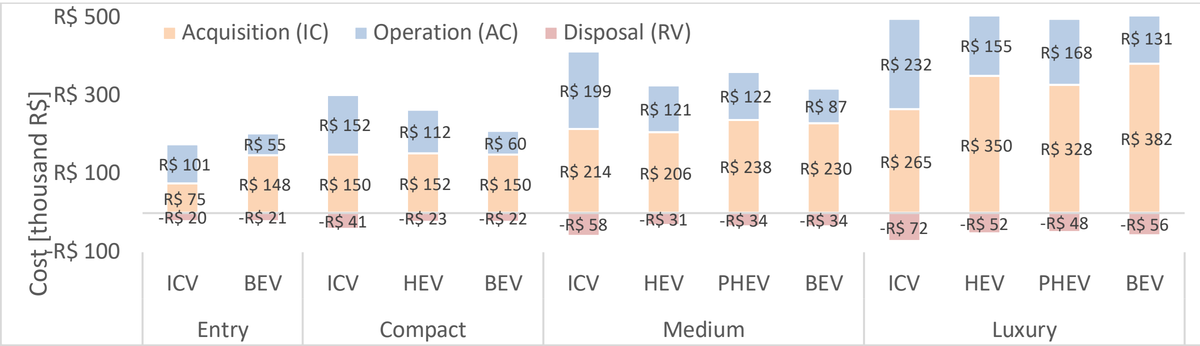


Figure 4 - Cost by phase for best sellers in Brazil

Figure 5 illustrates the TCO by component for best sellers in Brazil, making possible to identify the percentage of the TCO spent on depreciation, energy, insurance, maintenance, battery, and taxes. According to this figure, for vehicles in Table 22, BEVs depreciate around 70%; while ICVs 40%, HEV 60%, and PHEVs 62%. As mentioned previously, energy costs (fuel or electricity) are higher for ICVs (25%), followed by HEV (20%), PHEV (15%), and BEVs (5%). The percentage of the TCO spent on insurance and maintenance do not change significatively among the four propulsion systems, being the first around 14% and the second 3%; although the costs of these variables for ICVs are higher than for BEVs, as parameters in Table 10. Battery costs for PHEVs and BEVs represent around 1% and 3% of the TCO, respectively. Taxes are higher for ICVs (14%) than for BEVs (8%) due to government incentives for electric mobility.

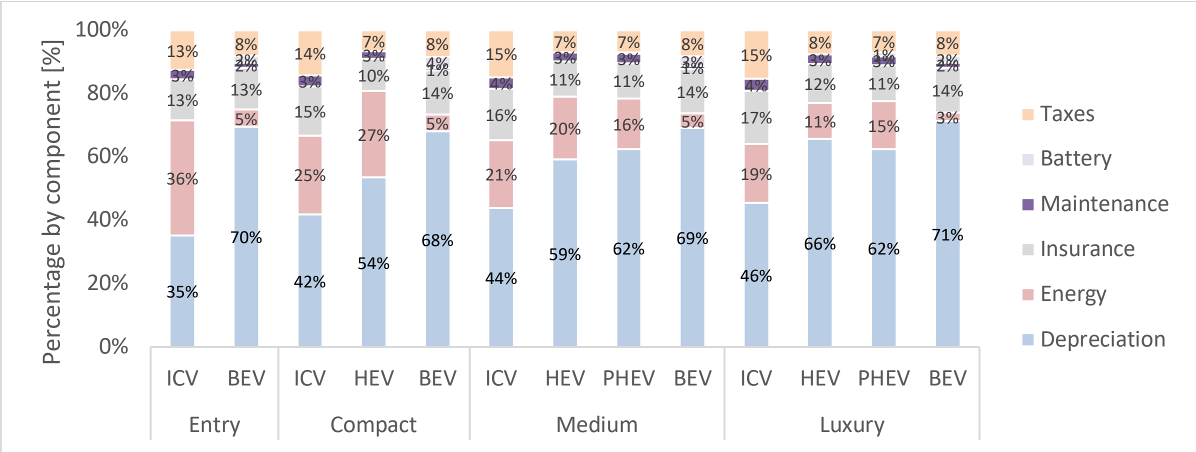
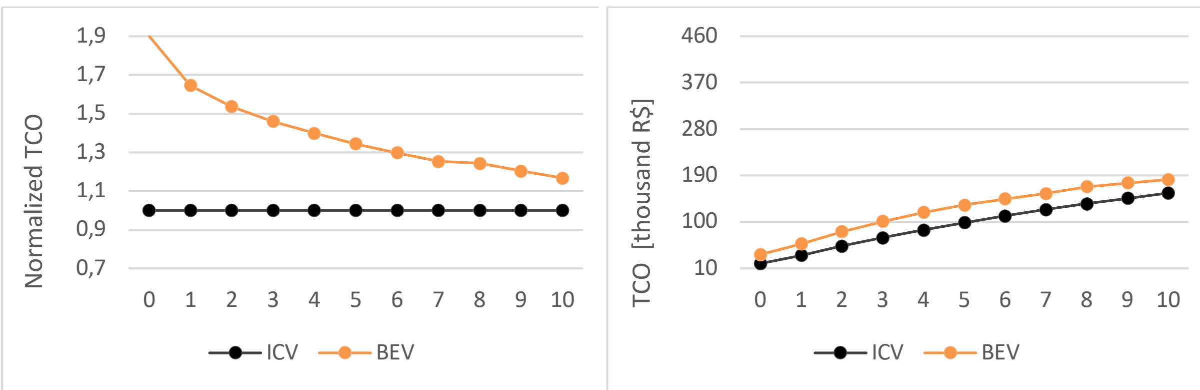
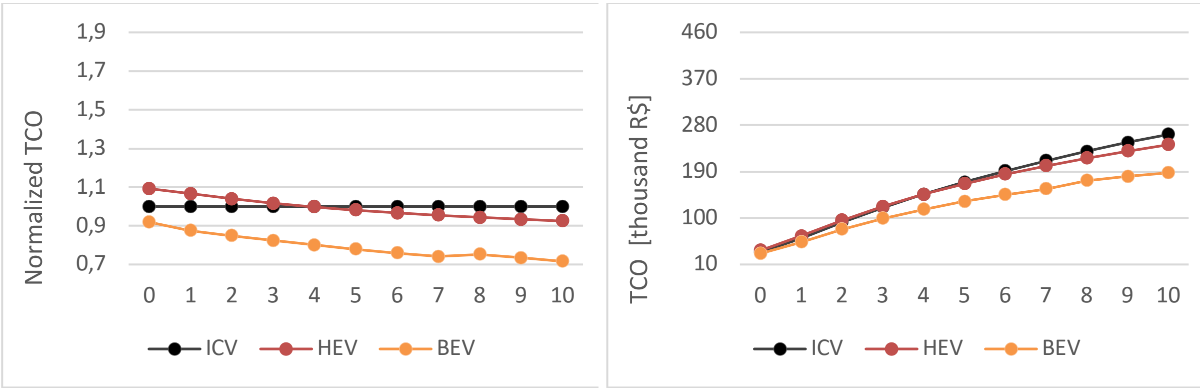


Figure 5 - TCO by component for best sellers in Brazil

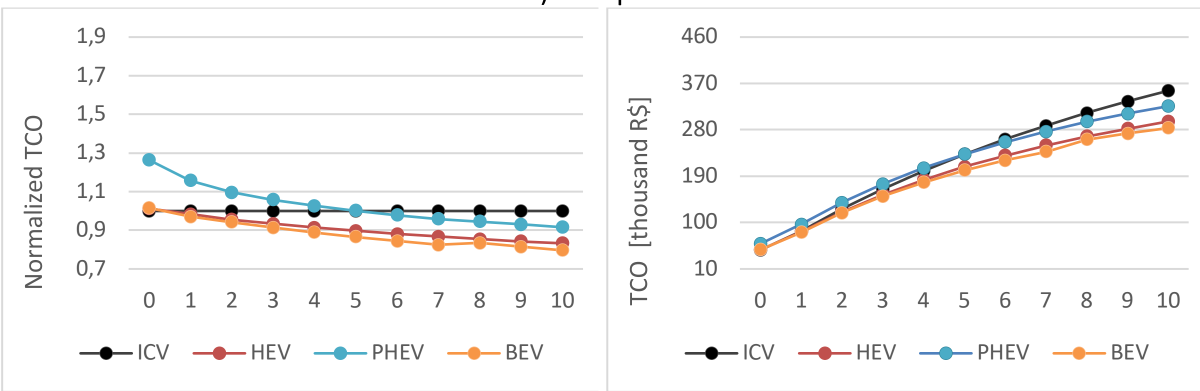
Finally, to conclude the best sellers in Brazil scenario, Figure 6 shows the TCO (normalized and annual values) of ICVs, HEVs, PHEVs, and BEVs throughout ten years. From this figure, it is possible to evaluate when the vehicles in Table 22 will have cost parity. For entry level there is no cost parity between ICVs and BEVs in the period analyzed in this study. Considering the compact level, the TCO of BEV is lower than of ICV throughout the entire period; while HEV reaches cost parity with ICV in the fourth period. For medium level, the TCO of HEV and BEV is lower than ICV almost the entire period; while PHEV reaches cost parity with ICV in the fifth period. Finally, for the luxury level HEV, PHEV, and BEV remain with a TCO higher than ICV during the 10 years of the analysis. Once again, the reason that TCO of EVs is lower than TCO of ICVs for compact and medium levels is that reasonable acquisition costs and low annual costs make EVs cost-competitive in relation to ICVs. It is important to highlight that, as Table 11 the BEVs from these levels have subsides from the retailer that reduce their initial and annual costs. After 10 years, the lowest final TCO is R$ 156,265.32 for ICV and R$ 182,440.75 for BEV (entry level) and the highest is R$ 425,568.89 for ICV and R$ 456,938.34 for BEV (luxury level).



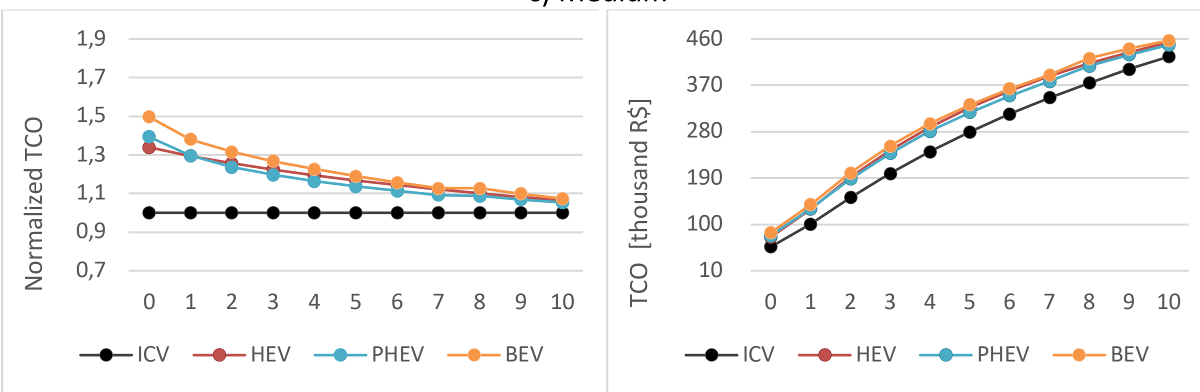
a) Entry



b) Compact



c) Medium



d) Luxury

Figure 6 – TCO (normalized and annual values) for best sellers in Brazil

5.3 TCO indicator across comparable and best-selling groups of vehicles for ICVs and BEVs

From figures 3 and 6, the TCO indicator of comparable and best-selling vehicles are analyzed. Extreme propulsion systems (ICVs and BEVs) are considered since they contemplate both groups.

For entry level, the TCO of BEVs is higher than of ICVs for both groups of vehicles throughout ten years. In this level, the normalized value variates from 1.94 to 1.21 for comparable vehicles (Figure 3a) and from 1.90 to 1.17 for best-selling vehicles (Figure 6a).

Considering the compact level, for comparable vehicles, the TCO of BEVs is also higher than of ICVs during the entire period. The normalized TCO goes from 2.52 to 1.67 (Figure 3b).

However, for best-selling vehicles the opposite occurs. The normalized value varies from 0.92 to 0.72 (Figure 6b).

Regarding the medium and luxury levels, for comparable vehicles, the TCO of BEVs starts higher (1.37 for medium level and 1.32 for luxury level) and finishes lower than of ICVs (0.91 for medium level and 0.96 for luxury level), as figures 3c and 3d. However, for best-selling vehicles, the TCO of BEVs is lower than of ICVs in the medium level (1.02-0.80) and higher in the luxury level (1.50-1.07), as figures 6c and 6d. As stated in sub-sections 5.1 and 5.2, the cost parity between ICVs and BEVs in Brazil can be reached; depending on the acquisition and annual costs, and subsides for purchase and operation of the vehicles.

5.4 Green Premium (GP) concept

The GP concept, also known as "energy transition costs", refers to the difference in cost between technologies with low or zero emissions and those with higher emissions [105]. Although, EVs can have emissions during their life cycle when the electricity generated to power them is not clean, in Brazil around 85% of electricity comes from clean and renewable sources. Therefore, in this sub-section, the GP value is presented for comparable and best-selling vehicles, as $TCO_{BEV} - TCO_{ICV}$.

Figure 7 shows the GP values between BEVs and ICVs for all levels of vehicles considered in this research. A negative GP means that the cost of acquisition, operation, and disposal of BEV is lower than of ICV. The negative GP values in this figure are justified by the combination of reasonable acquisition costs and low annual costs for BEVs in relation to the corresponding ICVs, as shown in Sub-sections 5.1 and 5.2.

Therefore, despite of the TCO of BEVs being lower than of ICVs in some cases, emphasized by the negative values in Figure 7, Brazilian consumers do not have access to this information. A comprehensive TCO model, calculated with recent data, for all segments of vehicles, and contemplating the current energy regulations (as presented in this research) was not available. This can justify the slow energy transition process in the country, being an important takeaway for stakeholders in Brazil.

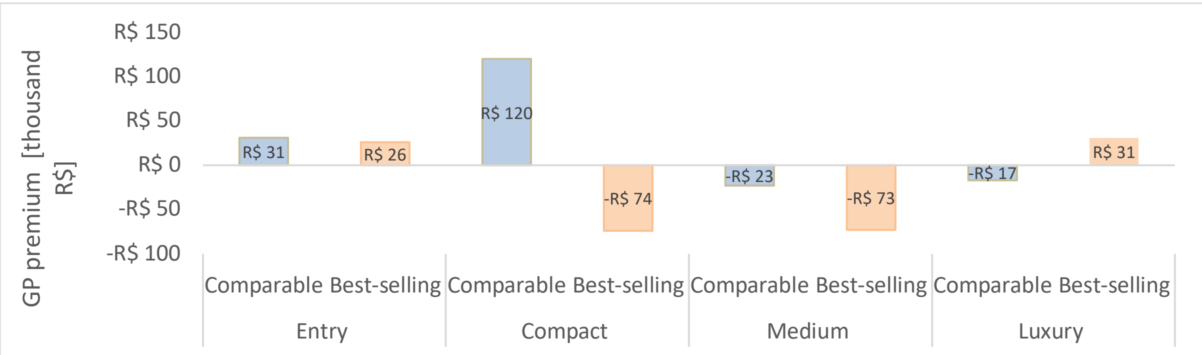


Figure 7 - GP values [thousand R$] between ICVs and BEVs for all levels

5.5 Discussion

The energy transition process requires a complete transformation of the mobility ecosystem. In addition to the cost-related factors considered in this research, other aspects, such as charging infrastructure, consumer behavior, and cultural attitudes play a pivotal role in EV adoption. The effects of these aspects on the diffusion of EVs has been discussed, for example, in [106, 107] for China and India context, respectively.

In Brazil, the growing acceptance of electric cars is associated with a preference for innovative and more sustainable alternatives and the positive experience of owners who report greater driving comfort, less noise, and a smoother ride. Besides, some states offer benefits, such as exemption from IPVA (vehicle tax), making the purchase of EVs more attractive.

However, beyond the purchase price, charging infrastructure is one of the main obstacles hindering the mass adoption of EVs in the country. EV users face significant obstacles, such as few charging stations, long lines, and defective chargers. Volvo, BYD, and GWM, which lead the market in Brazil and exclusively produce EVs, depend on an efficient charging network. These manufacturers can invest in charging infrastructure as an essential strategy to ensure their viability and success in the market. That was the case with Tesla in the USA, which created its "Superchargers" network, aiming to give customers greater security when purchasing the brand's vehicles.

Other success stories of EV diffusion come from Norway and China. Both countries are completely different in terms of size, location, climate, wealth, and culture; showing that rapid diffusion of EVs is not related to their specific characteristics. Thus, in order to learn from these countries' experiences, it is important to understand the actions taken by them.

Norway is the only country where the majority of cars sold are EVs. The government set the goal for all passenger cars sold to be zero-emission by the end of 2025. The Nordic country committed to tackle climate change by enforcing strong government policies, a robust infrastructure, and a cooperative population. The main actions done by the government to faster EV adoption in Norway were (i) making TCO of EVs become cheaper than TCO of ICVs when including all the tax breaks - EVs became the best financial choice for consumers; (ii) heavily investing in EV chargers - as a result, Norway has the most public fast chargers per capita of the world; and (iii) providing EVs' owners with added benefits - some examples are free parking, exemptions or reductions in road tolls, and access to priority bus lanes [63].

China sold more EVs in 2022 than the rest of the world combined. The country was behind others in ICVs production. Thus, the government saw EVs as a strategic investment for automobile manufacturing, starting early. The main actions done by the government to faster EV adoption in China were (i) including subsidies and tax breaks for both EV manufactures and consumers - preliminary with pilot cities around the country; (ii) encouraging the development of affordable EV models for costumers in China and exporting more expensive EVs globally - protecting internal production first and then focusing in economies of scale; (iii) investing in R&D of EV battery technology; (iv) installing many public charging points and offering non-monetary benefits to EV drivers - mostly at the city level [108].

Additionally, emerging markets, such as Brazil, Chile, Colombia, Indonesia, and Mexico have a large potential to reduce CO_2 emissions by transitioning to EVs. Some of these countries have taken action in that direction. For example, the value-added tax reduction in Indonesia and the tariff exemption for imported BEVs in Mexico have been key for these countries in the early adoption of EVs by reducing cost barriers, particularly the higher upfront cost of EVs relative to ICVs [18].

Therefore, government leadership has shown to be fundamental to faster EV adoption. By establishing clear targets, administrations can guide and support the growth of the market. Brazil has several possibilities for a low-carbon economy compared to other nations. Observing the success of the countries cited previously the following strategies, aligned with international best practices, could be recommended for Brazilian stakeholders:

- Considering the well-established infrastructure for the production and distribution of biofuels in the country: encourage EV manufactures to focus on flex-fuel hybrid vehicles. This would enable a strategic path to energy transition while maintaining benefits of the existing infrastructure.

- Considering the potential for solar energy and the important growth in adoption of photovoltaics systems due to recent policies: create an integrated regulation that brings economic benefits for recharging EVs at home using solar photovoltaic systems. This would enhance overall environmental benefits for both EVs and solar energy.

- Considering the large territory and extensive road network: expand charging infrastructure. This would make consumers with "range anxiety" to feel confident and safe for purchasing an EV and going for longer trips.

- Considering inequality and gap in social classes: encourage manufactures to produce cheaper priced EVs. This would favor the spread of technology including population with lower purchasing power.

- Considering apartments, condominiums, and older buildings frequent in larger cities: update the safety regulations of charging station installations, focusing on the standardization of chargers. This would ensure reliable and resilient energy networks.

- Considering population density and pollution in important hub cities: set goals for the percentage of electric buses for public transportation in cities' fleet. This would better traffic and air, enhancing overall life quality.

- Considering EV technology is incipient: keep subsidies and tax reductions. This is important for any new technology to be competitive in early stages. Targets can be set for the end of benefits once the objective is achieved.

- Considering public knowledge about new technologies: implement information campaigns to raise awareness of the EV ownership benefits. This would be possible by showing TCO data as done in this research. In general, consumers compare vehicles by upfront purchase price, this means costs associated with owning and operating a vehicle over its lifespan are not considered. The TCO information could be displayed with the National Energy Conservation Label affixed to vehicles' windows. This would enable consumers to make purchasing decision more assertively while industry would be stimulated to produce increasingly efficient products.

These measures would allow the country to better manage the pace of electrification in line with the development of global industry, without the need to commit to a specific route. It is important to note that some of these strategies are slowly taking place in the country. Toyota, for example, invested in factories in Indaiatuba and Sorocaba for the launch of Corolla flex-hybrid in 2019 and Corolla Cross flex-hybrid in 2021. BYD, one of the world's largest EV manufacturers, has announced that it will begin production of its cars in Bahia, some of which, with flex-fuel hybrid technology.

The study of the factors and variables that can influence the purchase of EVs is extremely important, as it makes it possible to implement effective public policies to promote the technology. The growth in the EV market is usually related to political incentives and the creation of bills designed to encourage consumers [109]. In Brazil, the government measures to promote EVs are mixed with measures to promote green technologies in general. That means that many policies may contribute to the EV segment, although they are not directly aimed at this objective. Examples of this are promotion of energy efficiency and reduction of greenhouse gas emissions [110]. This is demonstrated by Table 1 that shows the history of policies aimed at clean and sustainable transportation in Brazil.

General measures that are corelated to the theme, but don't specifically stimulate EVs can be cited as indirect measures. Examples from Table 1 are: (i) Proconve-1986, which defines the first emission limits for vehicles, thereby promoting the improvement of air quality forcing readjustment and the introduction of new technologies; (ii) PNMC-2009, which establishes targets for reducing greenhouse gas emissions serving as a basis for developing public policies aimed at technological development, energy efficiency, and environmental protection linked to the low-carbon economy; (iii) PBEV-2008, which enables the comparison of vehicles increasing consumer awareness and stimulating technical standards in relation to energy efficiency and fuel consumption; and (iv) Inovar Auto-2012, which promotes energy efficiency in engines produced in Brazil encouraging the reduction of emissions from new vehicles. As these are general measures usually, they are not noted by the end consumer, however they impact the entire automotive industry.

Specific actions that stimulate EVs can be cited as direct measures. These include: (i) BNDES Climate Fund, which enables the financing of various actions related to climate change offering the possibility of financing activities related to EVs in Brazil; (ii) Camex-2014, which has reduced the prices of EVs in the national market by establishing specific import taxes. Decree nº 9.442/2018 which reduced tax on industrialized products for electric and hybrid vehicles; (iii) Aneel nº 819/2018, which provides the first regulation on EV recharging for parties interested in providing this service; and (iv) Rota 2030/Mover, which promote the expansion of investments in energy efficiency, include minimum recycling limits in vehicle manufacturing and charge less tax to those that pollute less. As these are direct measures, they affect the price of the final product and therefore have a greater impact in consumer's choice.

6. Conclusion, Limitations, and Future Works

Considering the Brazilian context, this paper presents the development of a comprehensive TCO model applied for two sets of vehicles: four comparable pairs of ICVs and BEVs (same model and manufacture) and thirteen best-selling ICVs, HEVs, PHEVs, and BEVs (similar in terms of size, features, and price - as much as possible). The entry, compact, medium, and luxury levels are considered. In total, twenty-three scenarios from six case studies are evaluated. The six case studies contemplate: (1) comparable pairs - baseline, (2) comparable pairs - changing behavior parameters, (3) comparable pairs - excluding government subsidies, (4) comparable pairs - extreme positive scenario for EVs, (5) comparable pairs - extreme negative scenario for EVs, (6) comparable pairs - changing discount rates, and (7) best-selling vehicles. Energy costs (EC), annual costs (AC), and total cost of ownership (TCO) are the main analyzed costs.

Overall, considering all twenty-three scenarios, EC and AC are high for ICVs, intermediate for HEVs and PHEVs, and low for BEVs. For EC, that happens because the energy efficiency of ICVs is lower than of EVs, in addition to the fact that gasoline and ethanol are more expensive than electricity. Considering AC, the justification goes beyond energy efficiency and price. Maintenance and insurance costs, for example, which also make up AC are more expensive for ICVs than for EVs. Moreover, AC contemplate subsidies that only benefit EVs.

Regarding TCO, for comparable pairs, TCO of BEVs are higher than of ICVs in the entry and compact levels; the opposite occurs in the medium and luxury levels. The reason is that, in the entry and compact levels, the acquisition cost of BEVs is almost two/three times the acquisition cost of their respective ICVs. However, in the medium and luxury levels, the acquisition cost of ICVs and BEVs are closer, around 20-30% higher for BEVs.

For best sellers, TCO value is high for BEVs, intermediate for HEVs and PHEVs, and low for ICVs in the entry and luxury levels; being the contrary for ICVs and BEVs in the compact and medium levels. The justification is that, in the entry and luxury levels the acquisition cost of BEVs is almost two times the acquisition cost of ICVs. However, in the compact and medium levels, the acquisition cost of ICVs, HEVs, PHEVs, and BEVs are similar, varying less than 16%. Moreover, BEVs from these levels have subsides from the retailer that reduce their initial and annual costs.

Therefore, the overall conclusion shows that currently there are scenarios in which EVs are cost-competitive in relation to ICVs in Brazil, depending on energy efficiency, acquisition cost, and retailers' subsidies of the considered vehicles. Other factors significantly affect the attractiveness of EVs in relation to ICVs, such as consumer behavior and government subsidies. For example, not charging the vehicle at home (α = 0%) and long annual distance traveled (VKT = 60,000 km/year) make TCO of all BEVs higher than their respective ICVs. Therefore, BEVs can be cost-competitive when it is possible to charge them at a subsidized price, mainly benefiting long-distance consumers.

In addition, the simultaneous exclusion of government subsidies (for example $ASE = 0$ and $IPVA$ = 4%), makes AC of BEVs higher than their respective ICVs for vehicles with a high acquisition cost and low energy efficiency; and TCO of all BEVs higher than their respective ICVs. That shows how important a combination of government subsidies is to stimulate electric mobility and reinforces the influence of acquisition cost and energy efficiency on BEV attractiveness.

Lastly, extreme positive and negative scenarios for EVs are examined, considering consumer behavior and government subsidies at the same time. In an extreme positive scenario for EVs, TCO of BEVs is higher than their respective ICVs for all levels when VKT = 5,000; while the opposite occurs when VKT = 60,000. Extreme negative scenario for EVs makes TCO of BEVs higher than ICVs for almost all levels, regardless of the VKT value. Therefore, neglecting cost-reducing behaviors with EVs and eliminating government subsidies, simultaneously, can delay the transition process towards to sustainable mobility.

It is worth remembering that Brazil is among the major CO_2 emitters, its demand for diesel fuel has grown in recent years, and around 85% of its electricity comes from clean and renewable sources; making EVs a sustainable solution in the country. Moreover, EVs can contribute with the United Nations' global Sustainable Development Goals (SDGs), especially SDG-7: Clean energy, SDG-11: Sustainable city, and SDG-13: Climate action.

The methodology presented can be adapted to any country. Results depend on the input variables, parameters, assumptions, and context of the country. For this reason, they are specific for each research. In summary, for the analyzed case studies and considering all twenty-three scenarios, in terms of cost, ICVs outperform BEVs in 9 scenarios, ICVs and BEVs tie in 12 scenarios, and BEVs outperform ICVs in 2 scenarios.

Therefore, this research presents an updated conclusion about the transition process towards to sustainable mobility in Brazil, showing that currently there are scenarios in which EVs are cost-competitive in relation to ICVs. In order to accelerate this process, actions to reduce purchasing price of EVs, improve their energy efficiency, and enable recharging for reasonable prices (whether at home or public places) are recommended. That can be done, for example, through political incentives, which act as promotional tools to encourage the ownership of EVs.

Thus, this paper fills existing literature gap by presenting a detailed TCO model, for the Brazilian context, employing recent data, considering all levels of vehicles, and contemplating the energy credit compensation system. The findings of this study contribute to stockholders by providing information and recommendation, particularly highlighting government policies as the key factor to faster EV adoption and TCO as a tool to be used by end consumer for comparison analysis. Our insights are relevant to Brazil's unique energy and transportation ecosystem, but can also be applied by other countries.

Limitations

Although the TCO analysis is important to evaluate the economic viability of EVs adopting, it is essential to know the limitations of this study. The main limitations of the results presented are related to the uncertainty of some model parameters, considering changes in the technological environment and future variables.

For example, the technology related to batteries regarding efficiency and recycling is not discussed in this paper. Since EVs market is incipient in Brazil, real-world testing is still under development. Therefore, data concerning battery efficiency is unclear. However, the best available information is adopted in this study (as described in Section 4) for battery price and capacity, as well as, rate of change in battery price; which are employed in the TCO model.

In addition, there is an inherent degree of uncertainty when modeling future costs; particularly for energy prices (fuel and electricity), depreciation, maintenance, insurance, and annual discount rate. For this reason, in order to develop scenarios with consistent and well-founded parameter sets, data were extracted from reliable literature references and official entities publications. All parameters and assumptions have been justified in Section 4. Even so, as known, the results from mathematical models vary depending on the input data.

Future Works

Five suggestions are presented as future works. Three of them contemplate environmental, social, and political aspects; two suggestions are related to new applications of the TCO model developed in this research.

For environmental approach the reduction of greenhouse gas emissions, air and noise pollution, and dependence on fossil fuels from EVs can be considered; as well as, their impact in the battery disposal. In this suggestion, the emissions from electricity generation should be examined in order to promote EVs as a sustainable option. For social aspects, the studies can include, for example, the EVs impact on transportation equity and justice. Regarding political approach, the intangible value of public charging infrastructure to EV owners must be incorporated in the TCO studies.

As far as the two new applications of the TCO model, the first one refers to analysis considering data from countries characterized by different regulatory and financial policies, cost structures, fleet composition, and urbanization levels. In this suggestion, the relationship between the costs of BEVs and their level of diffusion on the market can also be addressed. The second suggestion is related to evaluation of the TCO results employing data from used cars instead of brand-new vehicles. It worth to highlight that, for example, in Brazil, used vehicles market has historically a ratio of 2.5 to 3.5 times the size of the new ones.

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2.3 - Energy compensation mechanisms (net-metering) and their effects in the total cost of ownership of electric vehicles

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Abstract

The world is moving towards energy transition and sustainable transport. This research covers solar photovoltaic (PV) systems and electric vehicles (EVs). The objective is to evaluate the effects of energy compensation mechanisms on the total cost of ownership (TCO) of EVs in the Brazilian context. The methodology employs a detailed TCO model that considers biofuel and subsidies for electricity. The case studies contemplate four levels of vehicles (entry, compact, medium, and luxury) and four net-metering rules (previous, current, considered, and future). The results show the average, minimum, and maximum variations in energy costs (EC), annual costs (AC), and TCO of internal combustion vehicles (ICVs) and battery electric vehicles (BEVs) for each compensation mechanism. The effects of compensation mechanisms are highest in EC, followed by AC, and then by TCO. Considering all levels and average values, TCO variation from previous to current scenario is 1.6%, from previous to considered scenario is 4.3%, and from previous to future scenario is 6.8%. Therefore, although the effects of energy compensation mechanisms are more significant for *EC* and, to a lesser extent for *AC*, in the *TCO* it does not reach 7%.

Keywords

Energy Transition, Climate Change, Net-Metering Policy, Photovoltaic System, Electric Mobility, Sustainable Transport, Total Cost of Ownership.

Introduction

Climate change stands as one of the most important environmental challenges of the 21st century, driving the urgent need for an energy transition toward renewable and low-carbon sources. Solar energy, due to its abundance, plays a key role in this shift, enabling cleaner electricity and powering sustainable mobility solutions, such as electric vehicles (EVs). EVs reduce greenhouse gas emissions, particularly in the transportation sector, which remains one of the largest global contributors to climate change (UNEP, 2024). Therefore, integrating energy transition strategies with public policies focused on renewable energy sources and sustainable mobility is essential to meet global climate goals, such as those outlined in the Paris Agreement, while simultaneously promoting economic development and socio-environmental justice. It is in this context that this paper is developed.

This research derives from two previous journal papers, Leite et al. (2024) and Leite et al. (2025), conducted for the Brazilian system, as Figure 1. Leite et al. (2024) shows how the net-metering policies impact solar photovoltaic investments from the investor's point of view. A mathematical model of discounted cash flow was developed to calculate four financial viability indicators (discounted payback, net present value, internal rate of return, and levelized cost of electricity). Three net-metering rules (previous, considered, and current: Normative Resolution 482/2012, Regulatory Impact Analysis 003/2019, and Law 14.300/2022), three energy consumption levels (low, middle, and high), and four discount rates (5%, 10%, 15%, and 20%) were considered. The results showed that from the previous rule to the current one the return for investor, on average, decreased 5.77%. However, this reduction would be of 12.81% if the considered rule was adopted. For the thirty-six studies carried out, even in the worst case the solar photovoltaic (PV) investments remained viable. Therefore, the current net-metering rule is suitable for the present stage of development of the sector; minimizing the impacts for energy tariff, distribution companies, consumers, and prosumers.

Leite et al. (2025) evaluates electric vehicles attractiveness in relation to internal combustion vehicles (ICVs). In this research, EVs include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). The methodology contemplates the development of a comprehensive mathematical model to calculate the total cost of ownership (TCO) in net present value (NPV), including the country's specificities in terms of biofuels and net-metering. Two sets of vehicles were considered: four comparable pairs (vehicles from the same manufacture, same category, and same model) and thirteen best-selling (similar vehicles in terms of size, features, and price). In total, twenty-one vehicles were analyzed from entry, compact, medium, and luxury levels. For comparable pairs a sensibility analysis was carried out to behavior parameters, government subsidies, extreme positive/negative scenario for EVs, and discount rates. The results showed that there are scenarios in which EVs are cost-competitive in relation to ICVs in Brazil depending on subsidies from government/manufacturer, energy efficiency, and acquisition cost of the vehicles. For the twenty-three studies carried out, in terms of cost, ICVs outperform BEVs in 9 scenarios, ICVs and BEVs tie in 12 scenarios, and BEVs outperform ICVs in 2 scenarios.

This new research combines both previous journal papers, evaluating the effects of energy compensation mechanisms (Leite et al.,2024) on the TCO of EVs (Leite et al.,2025). The objective is to analyze the indirect impact of the Brazilian net-metering policies on the attractiveness of EVs in the country, relating energy transition and sustainable transport topics. Four net-metering rules are considered (previous, current, considered, and future: Normative Resolution 482/2012, Law 14.300/2022, Regulatory Impact Analysis 003/2019, and Future Policy). Four pairs of comparable ICVs and BEVs from entry, compact, medium, and luxury levels are studied (Renault: Kwid and E-Kwid, Peugeot: 208 and E-208, Peugeot: 2008 and E-2008, and BMW: X1 and E-X1). Thus, the background information on the PV regulation is acquired from Leite et al. (2024). The mathematical model to TCO calculation is obtained from Leite et al. (2025). Data and parameters for the model are extracted from both journal papers.

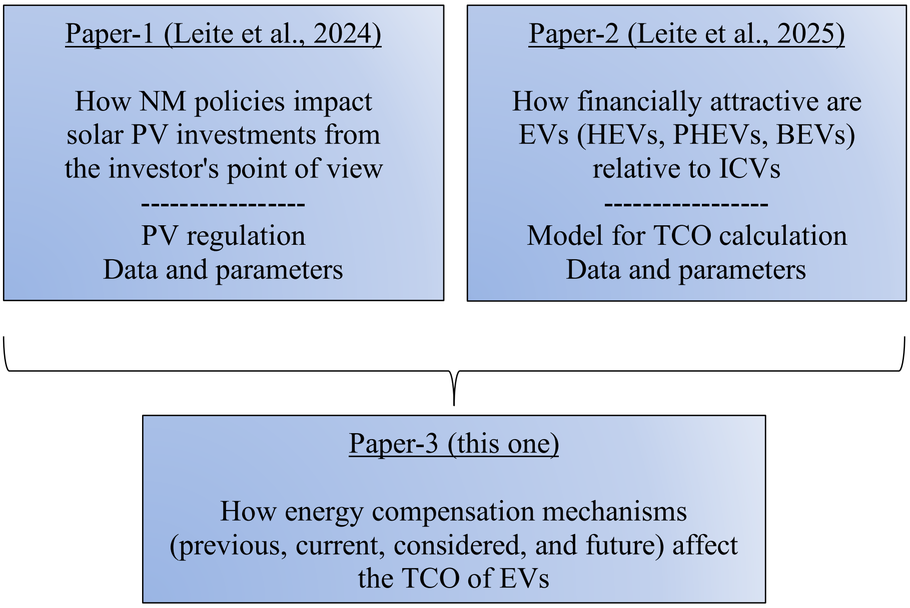

Figure 1 – Structure of the papers 1, 2, and 3

Methodology

As mentioned before, the TCO model employed in this research was presented in Leite et al. (2025). In summary, the TCO of a vehicle refers to all costs during its lifetime ($n = 1 \dots N$). These costs can be divided in three phases: acquisition – initial costs (IC), operation – annual costs, (AC), and disposal – residual value (RV).

Net present value (NPV) method was employed since the TCO formulation includes future costs. Thus, the investor's time value of money is taken into account. NPV estimates the current value of future costs, considering a discount rate (r_d) and the time when the costs occur (n).

Equation (1) presents the main formulation of the model, from Leite et al. (2025), for TCO calculation with NPV method. The first element, IC, includes all expenses to acquire the vehicle, such as manufacturer's suggested retail price (MSRP), taxes, registration fees, plate number, accessories, and costs for home charger (equipment, installation, and permit) - subsidies for vehicle and any monetary incentives for home charger should be subtracted of the IC. The second element, AC, corresponds to the sum of all recurrent expenses in every year $n \in [1, N]$ during the ownership period, for example, costs with energy (fuel and electricity), insurance, maintenance and repair are annual; as well as some taxes and fees - subsidies for electricity and vehicle must be subtracted of the AC. The third element, RV, is an estimative of how much the vehicle is worth at the end of ownership period (N) after depreciation over time.

$$TCO_i = IC_i + \sum_{n=1}^{N} \left[\frac{AC_{i,n}(VKT)}{(1 + r_d)^n} \right] - \frac{RV_{i,N}}{(1 + r_d)^N} \tag{1}$$

where:

i	type of the vehicle: ICV, or BEV;
TCO_i	total cost of ownership for vehicle type *i* [R$];
IC_i	initial costs for vehicle type *i* [R$];
n	specific number of a period [year];
N	total number of periods [years];
$AC_{i,n}$	annual costs for vehicle type *i* in the period n [R$];
VKT	annual vehicle kilometers travelled [km/year];
r_d	annual discount rate [%];
$RV_{i,N}$	residual value for vehicle type *i* in the last period, N [R$].

Beyond the main formulation, Equation (1), fifteen other equations make up the model. The calculation for annual subsidies for electricity (ASE) is replicated in Equation (2), since it is directly related with the objective of this research. As Leite et al. (2024), in Brazil, subsidies for electricity aim to promote distributed generation from renewable energy sources. For this, compensation mechanisms of energy, such as net-metering (NM), are available for solar PV system owners. In this case, the electricity added to the grid can be credited back. Thus, annual subsidies for electricity are subtracted from the energy costs of BEVs. They are computed as a percentage discount on the electricity price at home. Details about the methodology can be found in Leite et al. (2025).

$$ASE_{i,n} = [(\alpha_{i,n} * \ HElecPrice) * (1 + r_e)^n] * NM_{i,n} * VKT_{i,n} * EConsu_{i,n} \qquad (2)$$

where:

$\alpha_{i,n}$	percentage of electricity charged at home for i = BEV or PHEV in the period n [%];
$HElecPrice$	electricity price for home charge [R$/kWh];
r_e	rate of change in electricity prices [%];
$NM_{i,n}$	net-metering policy or percentage discount on the electricity price for *i* = BEV in the period n [%].
VKT	annual vehicle kilometers travelled [km/year];
$EConsu_{i,n}$	energy consumption for vehicle type i in the period n: fuel [l/km] and/or electricity [kWh/km].

Data, Parameters and Studies

Table 1 shows comparable vehicles data (same manufacture, model, category, and characteristics) of extreme propulsion systems (ICVs and BEVs) contemplating all levels (entry, compact, medium, and luxury). As Leite et al. (2025), MSRP corresponds to the price announced on the manufacturer's website in April/2024 - for models with different versions, the average price was adopted. Official consumption data were obtained from the Brazilian Vehicle Labeling Program (Gov, 2008) - for BEVs this information is presented in kilometer per equivalent liters (km/le). Maintenance data corresponds to the sum of the first five scheduled check-ups from the manufacturer's website in April/2024 - BMW vehicles are the only with no maintenance data, since the manufacture does not publish this information on its website. Battery capacity is available on the technical sheet of each vehicle on the manufacture's website in April/2024. For cost to replace a battery, according to BNEF (2024), the average price of battery is 139 $/kWh in 2023 - this corresponds to 685.27 R$/kWh, considering 1 dollar = 4.93 reais from the historical average of Abril/2023-2024 (Investing, 2024).

Table 1 - Vehicles data (Leite et al., 2025)

Level	Entry - Renault		Compact - Peugeot		Medium - Peugeot		Luxury - BMW	
Vehicle	Kwid	E-Kwid	208	E-208	2008	E-2008	X1	iX1
MSRP [R$]	75,000	140,000	89,166	236,000	135,000	170,000	300,000	360,000
Ethanol city [km/l]	10.8	-	8.6	-	7.7	-	10.9	-
Ethanol highway [km/l]	11.0	-	10.0	-	8.9	-	13.1	-
Gasoline city [km/l]	15.3	-	12.2	-	11.1	-	10.9	-
Gasoline highway [km/l]	15.7	-	14.1	-	12.7	-	13.1	-
Equivalent city [km/le]	-	52.7	-	37.8	-	38.0	-	35.3
Equiv. highway [km/le]	-	39.6	-	30.8	-	35.1	-	29.0
Maintenance [R$]	3,269	1,739	4,363	6,322	5,268	6,322	-	-
Battery capacity [kWh]	-	26.8	-	50.0	-	50.0	-	66.5
Battery price [R$]	-	18,365	-	34,263	-	34,263	-	45,570

Twenty-nine parameters are required for the detailed TCO model employed in this research. They are divided into 6 categories: general parameters; parameters by propulsion system; parameters related to discounts, subsidies, and monetary incentives; parameters related to energy costs; parameters related to taxes and fees; and parameters related to consumer behavior. All of them are defined and justified in the predecessor paper. The most important and most related to this research are replicated in Table 2.

Table 2 - Some parameters of TCO model (Leite et al., 2025)

Description	Variable	Value	References
Lifetime [years]	N	10	Sindipeças (2023)
Km travelled [km/year]	VKT	13,059	KBB (2019)
Discount rate [%]	r_d	7.71	BCB (2024)
National consumer price index [%]	$IPCA$	5.97	BCB (2024)
Annual subsidies for electricity [R$]	ASE	91.6% (n = 1) … 72.0% (N = 10)	Law (2022)
Ethanol price [R$/l]	$EthanPrice$	3.42	ANP (2024)
Gasoline price [R$/l]	$GasolPrice$	5.61	ANP (2024)
Electricity home price [R$/kWh]	$HElecPrice$	0.70	ANEEL (2024)
Electricity public price [R$/kWh]	$PElecPrice$	2.00	QR (2024)
Rate of change in fuel prices [%]	r_f	7.78	ANP (2024)
Rate of change in electricity prices [%]	r_e	6.21	CPFL (2024)
Electricity charged at home [%]	$\alpha_{i,n}$	85	ABRAVEI (2020)
Consumption adjustment [%]	$\gamma_{i,n}$	100	Gov (2008)
City trip [%]	$\theta_{i,n}$	54	Jonas et al. (2022)
Gasoline usage [%]	$\mu_{i,n}$	70	ICCT (2024)

The economic attractiveness of BEVs is examined through four studies presented in Table 3. Each one relates to a net-metering policy in the Brazilian context, as presented in Leite et al. (2024). Study-1 considers the normative resolution 482 of 2012 (previous scenario) in which 100% of electricity is credited back until 2045 for PV system owners before 2023 (REN, 2012). Study-2 corresponds to the law 14.300/2022 enforced nowadays (current scenario) with energy compensation varying from 91.6% to 72.0% (Law, 2022). Study-3 refers to regulatory impact analysis 003/2019 (considered scenario) that would compensate only one part of the electricity tariff, approximately 38% of the energy injected (AIR, 2019). Study-4 evaluates the BEVs attractiveness without energy compensation mechanism. For these four studies; ICVs and BEVs from entry, compact, medium, and luxury levels are evaluated. For the purpose of simplification, the range 91.6% - 72.0% will be referred as 72% from this point.

Table 3 - Studies analyzed in this research

Study #	Propulsion System	Net-Metering Rule	Levels
1	ICV x BEV	NM = 100% (previous)	Entry Compact Medium Luxury
2		NM = 91.6% - 72.0% (current)	
3		NM = 38% (considered)	
4		NM = 0% (future)	

Results and Discussions

Tables 4-7 and Figures 2-5 present EC, AC, and TCO variations in % and values in thousand R$ for entry, compact, medium, and luxury levels; respectively. Considering all tables and figures, as explained in the previous paper, EC and AC of all vehicles are higher for ICVs than for BEVs (second column, tables 4-7), since operation and maintenance costs of BEVs are lower than of ICVs. Besides, TCO of ICVs are more expensive than of BEVs for medium and luxury levels (second column, tables 6-7) because the acquisition costs of ICVs and BEVs are closer for these levels than for entry and compact levels, as MSRP in Table 1. Moreover, cost variations are highest for *EC*, followed by *AC*, and then *TCO* (third and fourth columns) since they are diluted as are introduced into the equations.

Table 4 and Figure 2 show the results for entry level. From ICV to best scenario for BEV (NM = 100%), EC and AC decrease 86.5% and 45.8%, respectively; while TCO increases 18.5% (third column).

Table 4 - EC, AC, and TCO variations for entry level

Variable [thous. R$]	ICV	BEV (NM)				Δ ICV →	Δ BEV (NM) 100% →		
		100%	72%	38%	0%	BEV (NM) 100%	72%	38%	0%
EC	52	7	10	15	20	-86.5%	42.9%	114.3%	185.7%
AC	96	52	55	61	66	-45.8%	5.8%	17.3%	26.9%
TCO	151	179	182	188	193	18.5%	1.7%	5.0%	7.8%

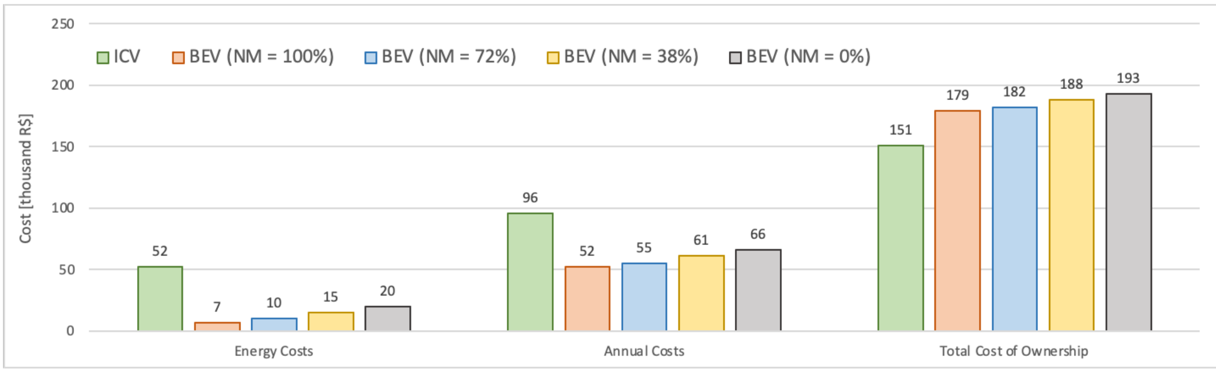

Figure 2 - EC, AC, and TCO values for entry level

Table 5 and Figure 3 present the data for compact level. From ICV to best scenario for BEV (NM = 100%), *EC* and *AC* fall 83.9% and 23.7%, respectively; while *TCO* rises 63.9% (third column).

Table 5 - EC, AC, and TCO variations for compact level

Variable [thous. R$]	ICV	BEV (NM)				Δ ICV →	Δ BEV (NM) 100% →		
		100%	72%	38%	0%	BEV (NM) 100%	72%	38%	0%
EC	62	10	15	23	30	-83.9%	50.0%	130.0%	200.0%
AC	114	87	91	99	107	-23.7%	4.6%	13.8%	23.0%
TCO	180	295	300	308	315	63.9%	1.7%	4.4%	6.8%

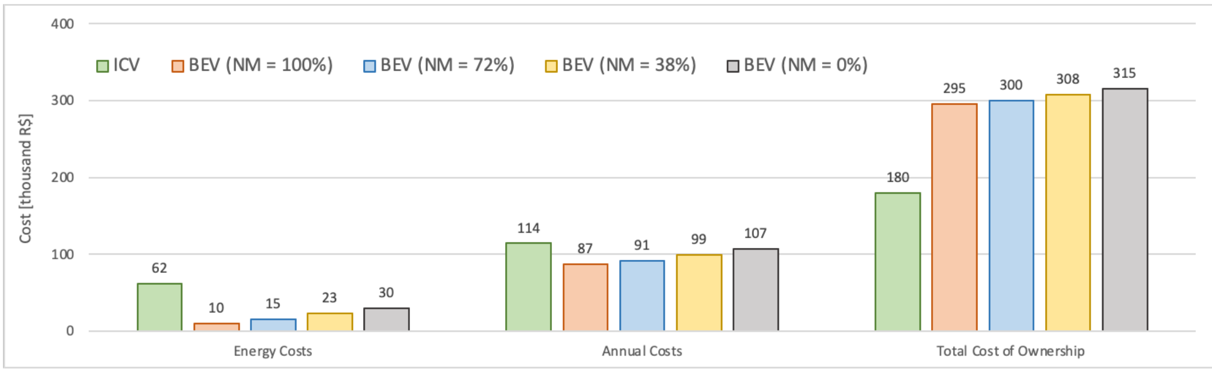

Figure 3 - EC, AC, and TCO values for compact level

Table 6 and Figure 4 display the results for medium level. From ICV to best scenario for BEV (NM = 100%), *EC*, *AC*, and *TCO* reduce 87.0%, 54.4%, and 11.0%, respectively (third column).

Table 6 - EC, AC, and TCO variations for medium level

Variable [thous. R$]	ICV	BEV (NM)				Δ ICV →	Δ BEV (NM) 100% →		
		100%	72%	38%	0%	BEV (NM) 100%	72%	38%	0%
EC	69	9	13	20	27	-87.0%	44.4%	122.2%	200.0%
AC	147	67	71	78	84	-54.4%	6.0%	16.4%	25.4%
TCO	246	219	223	230	237	-11.0%	1.8%	5.0%	8.2%

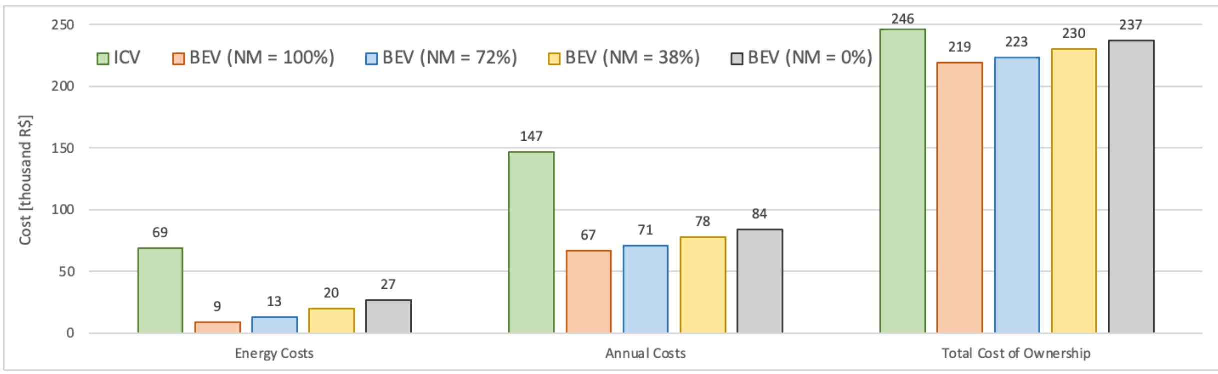

Figure 4 - EC, AC, and TCO values for medium level

Table 7 and Figure 5 exhibit the data for luxury level. From ICV to best scenario for BEV (NM = 100%), EC, AC, and TCO decrease 85.3%, 48.5%, and 4.8%, respectively (third column).

Variable [thous. R$]	ICV	BEV (NM) 100%	72%	38%	0%	Δ ICV → BEV (NM) 100%	Δ BEV (NM) 100% → 72%	38%	0%
EC	68	10	14	22	29	-85.3%	40.0%	120.0%	190.0%
AC	241	124	129	136	144	-48.5%	4.0%	9.7%	16.1%
TCO	460	438	443	450	458	-4.8%	1.1%	2.7%	4.6%

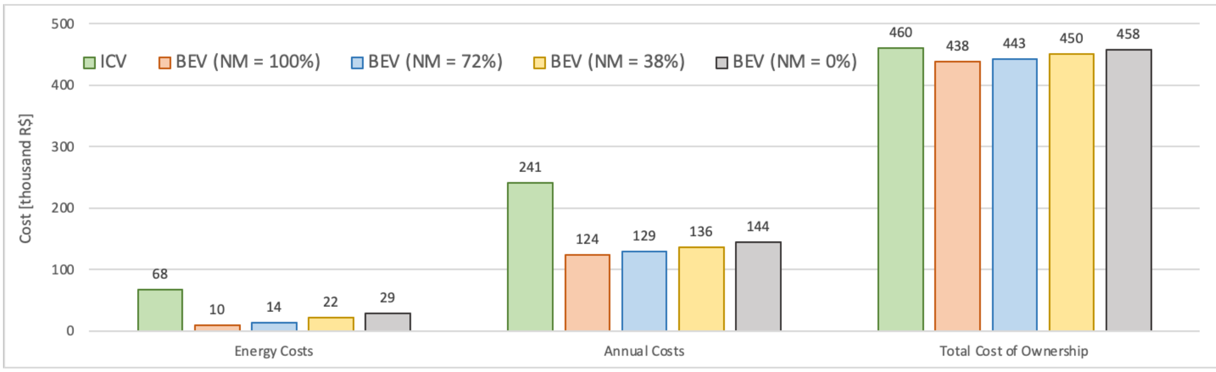

Figure 5 - EC, AC, and TCO values for luxury level

Table 8 summarizes the results found in this research, showing the effects of energy compensation mechanisms on the TCO of EVs in the Brazilian context. From 100% compensation to 72%, 38%, and 0% the variations of EC, AC and TCO are presented in average, minimum, and maximum values. Table 8 shows that:

- From previous to current scenario: EC range 40.0 – 50.0%, AC vary 4.0 – 6.0%, and TCO alter 1.1 – 1.8%.
- From previous to considered scenario: EC range 114.3 – 130.0%, AC vary 9.7 – 17.3%, and TCO alter 2.7 – 5.0%.
- From previous to future scenario: EC range 185.7 – 200.0%, AC vary 16.1 – 26.9%, and TCO alter 4.6 – 8.2%.

Table 8 - EC, AC, and TCO variations (average, minimum, and maximum) for all levels

Variable [thous. R$]	Average Values Δ BEV (NM) 100% → 72%	38%	0%	Minimum and Maximum Values Δ BEV (NM) 100% → 72%	38%	0%
EC	44.3%	121.6%	193.9%	40.0 - 50.0%	114.3 - 130.0%	185.7 - 200.0%
AC	5.1%	14.3%	22.9%	4.0 - 6.0%	9.7 - 17.3%	16.1 - 26.9%
TCO	1.6%	4.3%	6.8%	1.1 - 1.8%	2.7 - 5.0%	4.6 - 8.2%

Conclusions

This paper analyzes the indirect impact of the Brazilian net-metering policies on the attractiveness of EVs in the country, relating the energy transition and sustainable transport topics. Four net-metering rules (previous: NM = 100%, current: NM = 91.6 - 72.0%, considered: NM = 38%, and future: NM = 0%) and four pairs of comparable vehicles (ICVs x BEVs) from different levels (entry, compact, medium, and luxury) are evaluated.

As expected, the effects of compensation mechanisms are highest in EC, followed by AC, and then by TCO; as they are diluted in the model equations. EC and AC of all vehicles are higher for ICVs than for BEVs, since operation and maintenance costs of BEVs are lower than of ICVs. Besides, TCO of ICVs can be more expensive than of BEVs, depending on the BEV acquisition costs - specially MSRP. Therefore, the combination of reasonable acquisition costs and low annual costs for BEVs can lead to a lower TCO in relation to the corresponding ICVs.

The results of this research show that from previous to current energy compensation rule the average variations of EC, AC, and TCO are 44.3%, 5.1%, and 1.6%; respectively. These values, from previous to considered compensation rule, are 121.6%, 14.3%, and 4.3%; respectively. Finally, from previous to future energy compensation rule, the average variations of EC, AC, and TCO are 193.9%, 22.9%, and 6.8%; respectively.

Considering the current scenario as reference, all vehicle levels, and average values; return to a scenario in which 100% of electricity is credited back would reduce the TCO of BEVs by 1.6%. Adopt a mechanism that would compensate only one part of the electricity tariff (approximately 38% of the energy injected) would increase the TCO around 2.7%. Lastly, exclude the electricity subsidy (that means, do not compensate the energy injected into the grid) would increase the TCO of BEVs by 5.2% in relation to the current scenario.

In summary, assuming the current scenario as a starting point, for a change in regulation to any other evaluated scenario TCO ranges from -1.8% to 6.3%. Therefore, although the effects of energy compensation mechanisms are more significant for EC and, to a lesser extent for AC, in the TCO it does not reach 7%.

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3 - DISCUSSION

Energy transition requires a transformation that includes efforts towards increasing the use of renewable energy sources and of sustainable mobility ecosystems. In Brazil, renewable energy from solar photovoltaic (PV) systems grew in installed capacity after 2012 with ANEEL's Normative Resolution nº 482/2012, which regulated the distributed generation. The regulatory framework allowed individuals to generate their own electricity.

ANEEL has proposed changes on how energy credits are compensated in distributed generation systems. In short, the previous regulation established a net-metering (NM) system with 100% compensation (REN, 2012). The considered rule would compensate approximately 38% (AIR, 2019) of the energy injected. Lastly, the current net-metering allows energy compensation varying from 91.6% to 72.0% (Law, 2022).

The alternatives of energy compensation previously mentioned were employed in the first paper in order to evaluate their impact on PV investments. A mathematical model of discounted cash flow was developed to calculate discounted payback (DP), net present value (NPV), internal rate of return (IRR), and levelized cost of energy (LCOE) of solar photovoltaic investments. In total thirty-six scenarios were analyzed contemplating three net-metering rules (previous, considered, and current), three consumption levels (low, middle, and high), and three discount rates (5%, 10%, 15%, and 20%).

The results of Paper-1 show that net-metering rules has great impact on viability indicators, reducing the return on investment by more than 12%. Besides, net-metering policies affect the sensitivity of the investment in relation to discount rate, since the lower the energy compensation the greater the impact of the discount rate on the viability indicators (for example, the percentage variations in DP and NPV are smaller for NM = 100% than for NM = 38%). Lastly, technical and cost data of the projects also significantly impact the viability of investments (for example, the return for high consumption level in the most pessimistic scenario is higher than for the low consumption level even in the most optimistic scenario).

In regards to mobility ecosystems, in Brazil, general measures to promote sustainability, such as emission limits and energy efficiency standards, indirectly contribute to electric vehicles adoption. However, more direct actions, such as tax reductions on electric vehicles, are essential in stimulating the market. These measures can help the country align with global trends while addressing local challenges.

Purchase price is known to be the most relevant variable for the diffusion of electric mobility. It is also an important input for calculating the total cost of ownership (TCO). In the context of transport electrification, TCO has been employed to compare internal combustion vehicles (ICVs) and electric vehicles (EVs).

The second paper of the thesis presents the development of a comprehensive TCO model applied for two sets of vehicles: four comparable pairs of ICVs and battery electric vehicles (BEVs); and thirteen best-selling ICVs, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and BEVs. The entry, compact, medium, and luxury levels are considered. In total twenty-three studies are analyzed. Additionally, a sensitivity analysis was done for behavior parameters, government subsides, extreme positive/negative scenarios for electric vehicles, and discount rates.

The results in Paper-2 present energy costs (EC), annual costs (AC), and TCO for each vehicle analyzed. In general, EC and AC are high for ICVs, intermediate for HEVs and PHEVs, and low for BEVs; since operation and maintenance costs of EVs are lower than of ICVs. Besides, *TCO* of ICVs can be more expensive than of BEVs, depending on the BEV acquisition costs - specially purchase price. In the scenarios evaluated that happened, for example, with comparable pairs in the medium and luxury levels and with best-selling in the compact and medium levels.

The third paper presented in this thesis, as mentioned in the Introduction section, derives of a combination of the first two. It brings the analysis of the indirect impacts of the Brazilian net-metering policies on the attractiveness of EVs in the country, relating the energy transition and sustainable transport topics. Four net-metering rules (previous = 100% compensation, current = 91.6% - 72.0% compensation, considered = 38% compensation, and future = 0% compensation) and four pairs of comparable vehicles (ICVs x BEVs) from different levels (entry, compact, medium, and luxury) are evaluated.

The results of Paper-3 show that cost variations are highest for EC, followed by AC, and then TCO; as the effects of the compensation mechanism are diluted in the fifteen equations that make up the mathematical model. Starting from the previous scenario for any other scenario evaluated (current, considered, and future), the average variation in the total cost of ownership of BEVs is 1.6%, 4.3%, and 6.8%; respectively. Considering the current scenario as reference these values are -1.6%, 2.7%, and 5.2%.

Table 1 summarizes the three papers that make up this research. Issue (gray), methodology (orange), studies (green), and main results (blue) are presented for each one.

Paper-1

How NM policies impact solar PV investments from the investor's point of view.

Mathematical model of discounted cash flow to calculate PD, NPV, IRR, LCOE.

36 studies:

- NM rules (previous, considered, and current).
- Consumption levels (low, middle, and high).
- Discount rates (5%, 10%, 15%, and 20%).

Previous → current = IRR ↓ 5.77%.
Previous → considered = IRR ↓ 12.81%.

Even in the worst case the solar PV investments remain viable.

Paper-2

How financially attractive are EVs (HEVs, PHEVs, BEVs) relative to ICVs.

Mathematical model to calculate the TCO in NPV, considering biofuels and net-metering.

23 studies:

Entry, compact, medium, and luxury levels:

- Four pairs of comparable vehicles (ICVs x BEVs).
- Thirteen best-selling vehicles (ICVs x HEVs, PHEVs, BEVs).

ICVs outperform BEVs → 9 scenarios.
ICVs and BEVs tie → 12 scenarios.
BEVs outperform ICVs → 2 scenarios.

EVs can be cost-competitive in relation to ICVs depending on subsidies, energy efficiency, and acquisition cost of the vehicles.

Paper-3

How energy compensation mechanisms affect the TCO of EVs.

Mathematical model to calculate the TCO in NPV, considering different net-metering rules.

4 studies:

- NM rules (previous, current, considered, and future).

Entry, compact, medium, and luxury levels:

- Four pairs of comparable vehicles (ICVs x BEVs).

Previous → current, considered, or future = TCO variation: 1.6%, 4.3%, 6.8%
Current → previous, considered, or future = TCO variation: -1.6%, 2.7%, 5.2%.

Although the effects of energy compensation mechanisms are more significant for EC and, to a lesser extent for AC, in the TCO it does not reach 7%.

Table 1 - Summary of the three papers that make up the thesis:
Issue (gray), methodology (orange), studies (green), and main results (blue).

4 – CONCLUSION

From Paper-1, it is possible to realize that changes in the energy compensation mechanisms impact the economic viability of solar PV investments. Restricted compensation impacts the profitability of the investment. On the other hand, allowing compensation of all energy injected into the grid, in which the prosumer does not pay for the use of the grid, can harm concessionaires and consumers who have not invested in their own power generation. Thus, Brazilian Electricity Regulatory Agency (ANEEL) has worked to create a model that keeps the solar sector growing and minimizes the impacts for energy tariff, distribution companies, consumers, and prosumers.

The results show that from the previous to current rule the return for investor, on average, decreased 5.77%. However, this reduction would be of 12.81% if considered rule was adopted. For the 36 studies carried out, even in the worst case the investment remains viable, with positive NPV and DP of 7.34 years (considered reasonable by most companies).

Therefore, the PV regulation adopted in Brazil is suitable for the current stage of sector development. Although the net-metering policies show a reduction in the percentages of energy compensation since 2023, investments in PV systems remain sustainable in the country. This contributes to the growth of both distributed generation and solar source.

According to Paper-2, in the last years, the combination of government subsidies (electricity and tax reduction) and competitive prices from some manufactures have contributed to boost EV acceptance in Brazil. However, problems with charging infrastructure (few charging stations, long lines, and defective chargers) are the main obstacles hindering the mass adoption of EVs in the country.

For the analyzed case studies and considering all twenty-three scenarios in Paper-2, in terms of cost, ICVs outperform BEVs in 9 scenarios, ICVs and BEVs tie in 12 scenarios, and BEVs outperform ICVs in 2 scenarios. It is worth remembering that Brazil is among the major CO_2 emitters, its demand for diesel fuel has grown in recent years, and around 85% of its electricity comes from clean and renewable sources; making EVs a sustainable solution in the country.

The overall results show that currently there are scenarios in which EVs are cost-competitive in relation to ICVs in Brazil, depending on acquisition cost and energy efficiency. Other factors significantly affect the attractiveness of EVs in relation to ICVs, such as consumer behavior and government subsidies. For example, not charging the vehicle at home and long annual distance traveled make TCO of all BEVs higher than their respective ICVs.

Additionally, the exclusion of government subsidies makes TCO of all BEVs higher than their respective ICVs. Therefore, neglecting cost-reducing behaviors with EVs and eliminating government subsidies, simultaneously, can delay the transition process towards to sustainable mobility.

Paper-3 is a combination of Paper-1 and Paper-2. It employs PV regulation from Paper-1, mathematical model from Paper-2, and data/parameters from both. Paper-3 shows that the energy compensation mechanisms affect more significantly EC (28 times the TCO), followed by AC (3 times the TCO), and then TCO.

Considering the current scenario as reference and average values; returning to a scenario in which 100% of electricity is credited back would reduce the TCO of BEVs by 1.6%. Adopt a mechanism that would compensate only one part of the electricity tariff (approximately 38% of the energy injected) would increase the TCO around 2.7%. Lastly, exclude the electricity subsidy (that means, do not compensate the energy injected into the grid) would increase the TCO of BEVs by 5.2% in relation to the current scenario.

In summary, assuming the current scenario as a starting point, a change in regulation to any other evaluated scenario varies the TCO from -1.8% to 6.3%. Therefore, although the effects of energy compensation mechanisms are more significant for EC and, to a lesser extent for AC, in the TCO it does not reach 7%.

Regarding the final considerations, as can be seen from the papers, government incentives play a critical role in accelerating the adoption and development of emerging technologies, such as solar PV and EVs. These technologies often face significant barriers to widespread deployment, including high initial costs, infrastructure limitations, and market uncertainty. Government incentives can help overcome these challenges by providing financial support, policy frameworks, and regulatory environments that promote investment and consumer adoption.

Therefore, government leadership has shown to be fundamental to faster PV and EV adoption. By establishing clear targets, administrations can guide and support the growth of the markets. Brazil has several possibilities for a low-carbon economy compared to other nations. Observing the success of some countries aligned with international best practices, some recommendations for Brazilian stakeholders were listed in the papers. Furthermore, the limitations of each research, as well as suggestions for future work, can be found at the Conclusion section of each paper.

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