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Climate Change Mitigation Policies in the Transportation Sector in Rio de Janeiro, Brazil

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Abstract: This study analyzes climate change mitigation policies focused on light-duty electric vehicles (LDEVs) in the transportation sector in Rio de Janeiro state, Brazil, in the 2016–2050 period. We use the Open Source Energy Modeling System (OSeMOSYS) to analyze scenarios that consider greater uptake of LDEVs in different time frames, implementation of a CO_2 emission restriction policy, exclusion of fossil fuels from the power mix, and a combination of these policies. We find that carbon pricing, along with higher rates of LDEVs adoption, causes the highest emission reductions (up to 47%), albeit at higher costs. LDEVs become the preferred vehicle technology as soon as they reach cost parity with internal combustion engine vehicles in different scenarios. Greater LDEVs uptake, however, leads to increased electricity consumption (up to 3%), which is provided by fossil fuels when there is no emission restriction policy. If restrictions are placed on the expansion of fossil fuel power plants, fewer LDEVs are adopted (up to less than 26%) because there is not enough electricity to supply the demand. Given the state's power mix in 2016 (58% provided by fossil fuels), investment in zero-carbon energy is necessary for mitigation policies in the transportation sector to be effective.

Keywords: climate change mitigation; transportation sector; energy modeling and policy; Rio de Janeiro state

1. Introduction

Human-induced climate change is one of the biggest challenges facing humankind today. Although science has provided many answers on how to slow it down, society is still struggling to implement measures that can achieve this outcome. Moreover, decarbonizing some energy end-use sectors is more straightforward than other measures. For instance, increasing the use of renewable energy in electricity generation will enable the decarbonization of power generation. For other sectors of the economy, however, decarbonization is more complex. Transportation is one such sector due to, among other things, the high number and dispersion of agents, as well as high-technology lock-in to fossil fuel-based engines [1].

Several studies have investigated how to pursue decarbonization in transportation. Bataille et al. [2] designed net-zero deep decarbonization pathways in Latin America and concluded that decarbonization is reached in the transportation sector through a mix of urban planning, mode shifting, electrification of buses and passenger vehicles, and alternative net-zero liquid fuels (e.g., sustainable biodiesel and ethanol). The same approach for China [3] concludes that carbon intensity improvements toward cleaner alternative fuels, such as renewable electricity, biofuels, and hydrogen, are mainly responsible for mitigation efforts in the country. For the 28 countries of the European Union (pre-Brexit), Haasz et al. [4] studied methods to decarbonize the transportation sector, and found that electrification will play a key role, especially after 2030. In Brazil, Goes et al. [5] found that investments in electromobility and infrastructure to decarbonize transportation are more cost-effective than biofuels.

From the supply side, current efforts to decarbonize the transportation sector consider it necessary to increase engine efficiency and to foster the use of low-carbon fuels; from the demand side, measures must encourage changes in travel behavior towards more sustainable mobility solutions [6]. These solutions are not mutually exclusive. For instance, a broader approach to deeply decarbonize the transportation sector can utilize electric vehicles and modal switches in passenger transportation [7,8], while adopting a mix of electrification, biofuels, and hydrogen in freight transportation.

Among the decarbonization alternatives sought from the supply side, electrification has gained terrain for two reasons: first, electric motors are much more efficient than internal combustion engines [9]; therefore, overall energy efficiency of fleet usage would increase as a result of a switch to electric vehicles. Second, renewable electricity as an energy source can substantially reduce transportation's carbon footprint. Indeed, Dominković et al. [10] conducted a literature review to assess the contributions of biofuels, hydrogen, synthetic fuels, electrofuels (produced from CO_2 and water electrolysis), and electricity to the transition to renewable transportation. They concluded that electrification showed the greatest benefits and should be the focus of the transport transition. Moreover, higher fleet efficiency leads to lower final energy demand in the transportation sector. Finally, a mix of biofuels and synthetic fuels would supply the remaining transportation fuel demand.

Several other authors have studied the role of electrification in decarbonizing the transportation sector, especially in passenger transportation. Teske et al. [11] studied the implications of high renewable energy penetration for urban energy and transport systems, and found that, in such a scenario, transport energy demand would be lower due to a drastic shift to electric mobility, accompanied by a phasing out of combustion engines and a modal shift in favor of urban public transport. A study by Zhang et al. [12] analyzed how several low-carbon transport policies, such as electric vehicles, speed regulation, pedestrian-friendly design, and bicycle-oriented development, contributed to decarbonization and concluded that electric vehicles have the most significant emissions reduction. Lorenzi and Baptista [13] performed a scenario analysis to assess the promotion of renewable energy sources in the transportation sector in Portugal and found that electric vehicles would substantially reduce total energy consumption and greenhouse gas emissions. Furthermore, Brozynski and Leibowicz [14] studied how to decarbonize power and transportation at the urban level and discovered that the optimal decarbonization pathway has two stages: reducing carbon intensity in the power sector, followed by electrifying transportation. Further, Glitman, Farnsworth, and Hildermeier [15] assessed the role of electric vehicles (EVs) in a decarbonized economy and concluded that with proper integration with the power sector, EVs can be useful tools in such an economy.

Regarding technology comparison, Ahmadi [16] conducted a life-cycle emission and cost comparison among different powertrains of electric vehicles to assess their contribution to the decarbonization of transportation. The conclusion was that fuel cell electric vehicles (FCEVs) and full battery electric vehicles (BEVs) are "the most environmentally benign" options. Paulino, Pina, and Baptista [17] evaluated alternatives for the passenger road transport sector in Europe and found that compressed natural gas (CNG), biofuels, and electric vehicles show the greatest reduction in climate change. Finally, Hannula and Reiner [18] studied the role of biofuels, electrofuels, and BEVs in decarbonizing road transport and found that such technologies would require carbon and oil prices higher than USD 130/t CO_2 and USD 100/bbl, respectively, to become commercially viable relative to petroleum. Economies of scale in deployment and production, however, will potentially reduce these figures, as well as access to low-cost renewable electricity. Therefore, electrification of light-duty passenger vehicles appears to be an important measure to reduce emissions in the transportation sector (according to the Brazilian National Transit Authority (DENATRAN), light-duty vehicles refer to mopeds, scooters, motorcycles, tricycles, quadricycles, automobiles, utility vehicles, and pickup trucks, with total gross weight – PBT (peso bruto total) less than or equal to 3,500 kg [19]. In this paper, light-duty vehicles are automobiles).

In fact, the cost of electric powertrains has been falling in the past few years. Increased interest from both the demand and supply sides has contributed to a growth in the uptake of light-duty electric vehicles (LDEVs) and to a decrease in their acquisition cost. In the past decade, the cost of batteries—the main contributor to the price of LDEVs—has fallen by 87% [20], and it is expected that economies of scale in battery production will push this figure even further down in the future.

In this context, this study analyzes how the adoption of LDEVs and other policies, such as carbon pricing, can contribute to climate change mitigation by reducing emissions in the transportation sector. The case study for this work is the state of Rio de Janeiro (RJ) in Brazil. RJ was chosen because it is the second largest state in Brazil—a country where transportation, not power production, accounts for the most greenhouse gas emissions (GHG) in the energy sector. In RJ state, the transportation sector is actually the second largest overall GHG emitter [21]. This outcome is explained by a few facts: 87% of fuel consumed in road transportation is provided by fossil fuels (the remaining 13% is provided by ethanol [22]), and this mode accounts for 76% of transportation fuel consumption in the state [22]. Light-duty passenger vehicles account for 40% of fuel consumption within road transportation; freight accounts for 50% and heavy-duty passenger vehicles (buses) account for the remaining 10% [22–24]. In fact, 45% of RJ households owned a car for private transportation in 2016 [25]. In addition, the rate of vehicles per 1000 people in that year was 232, a value that would place RJ in 63rd place among 190 countries [26–28], ahead of other South American countries such as Chile and Uruguay. Therefore, given the weight of this mode in state transport, decarbonizing road transportation is equally a challenge and a great opportunity to reduce emissions for both the state and the country.

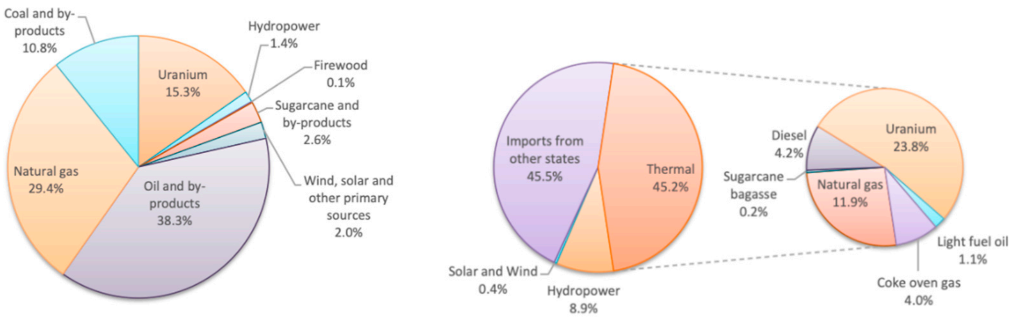
To assess how LDEVs can be used as a climate change mitigation policy, we model the energy sector of RJ state for a baseline year (2016), and we then analyze how mitigation policies, such as carbon pricing, along with greater uptake of electric vehicles, contribute to reducing carbon emissions in the 2016–2050 horizon at the lowest possible cost. We find that carbon pricing, along with higher rates of LDEVs adoption, causes the highest emission reductions, albeit at higher costs. Moreover, the sooner electric vehicles are adopted, the lower the overall system cost. In addition, as expected, higher uptake of LDEVs leads to more electricity consumption, which is provided by either the renewable or fossil fuel installed capacity. To assess transportation decarbonization in a 100% renewable power system, we run a final analysis in which electricity generation is completely supplied by renewables. In such a scenario, given the limitations of generating renewable electricity within Rio de Janeiro, there is a big uptake of imports. Nevertheless, because there is not enough electricity to supply both final electricity and transportation demands, these scenarios see a lower uptake of LDEVs. In conclusion, to fully decarbonize the transportation sector, Rio de Janeiro must expand its renewable generation capacity to other renewable energy sources—such as offshore wind and solar, hydrogen, and bioenergy.

The remainder of this paper is structured as follows: the rest of this section describes RJ state's energy system and light-duty passenger transportation sector; Section 2 explains the energy systems model that was used in this paper, details how RJ state's reference energy system (RES) was built, and describes the scenarios that were analyzed; Section 3 examines the results, while Section 4 closes this paper by discussing its findings.

1.1. *Rio de Janeiro State's Economy and Energy System*

In 2016, Rio de Janeiro was the third most populous state in Brazil, with a population of approximately 17 million people [27]. The state is the second largest economy in the country (only behind São Paulo state), being responsible for 10% of the Brazilian GDP (which in 2016 was USD 1.6 trillion) [29].

The industry and services sectors account for most of the state's economic activity (18% and 59%, respectively, in 2016) [30]. Figure 1 portrays Rio de Janeiro state's internal energy supply and electricity generation by source, which were 32 Mtoe and 56 TWh in 2016, respectively [22].



(**a**) (**b**)

Figure 1. Internal energy supply (**a**) and electricity generation by source. (**b**) Rio de Janeiro state—2016. Source: [22].

Brazil is an important oil and natural gas producer (ninth worldwide in 2016, eighth in 2019 [31]), as well as Rio de Janeiro state. As of 2016, Brazilian proved oil and natural gas reserves were 12,634 million barrels and 337,406 million cubic meters, of which 82% and 61%, respectively, were located in Rio de Janeiro [32]. RJ state produced 614,713 million barrels of oil and 16,613 million cubic meters of natural gas in 2016, accounting for 67% and 44%, respectively, of national production [22]. In 2016, there were two oil refineries and natural gas processing units in the state, with capacity to process 266,000 barrels of oil/day and 20,900,000 cubic meters of natural gas/day.

Oil and natural gas processed in the state supply not only the internal state demand but are also exported to other Brazilian states (except diesel, which needs to be imported to fulfill the internal demand. Regarding natural gas, although it is exported to other states, a small fraction is also imported from abroad. A fraction of crude oil is also imported from other countries) [22]. In 2016, RJ state's transportation sector consumed 2 million cubic meters of gasoline, 2.3 million cubic meters of diesel, and 881 million cubic meters of compressed natural gas (CNG) [22]. Oil products and natural gas were also consumed by thermal power plants to generate electricity, as shown in Table 1.

Table 1. Rio de Janeiro state's thermoelectric installed capacity and generation—2016. Source: [22].

Source	Installed Capacity (MW)	Generation (TWh)
Natural gas	4490	6.7
Diesel	129.4	2.4
Light fuel oil	490	0.6
Coke oven gas	21	2.3
Uranium	1990	13.4
Sugarcane bagasse	44	0.1
Total	7164	25.4

Rio de Janeiro state does not have coal reserves, which are located in the southern region of Brazil. All coal consumed in the state is thus imported [22]. Coal in RJ state is used in the steel and iron industry, where it is transformed into coal coke for consumption in high-temperature blast furnaces. In fact, only one power plant in the state uses coal products, which is a combined heat and power plant located in a steel mill. Coal coke is used in blast furnaces, and the high-temperature gases are used to generate electricity. Table 1 shows this power plant's installed capacity and electricity generated in 2016.

Brazil has two nuclear power plants located next to each other in Rio de Janeiro state. Table 1 lists their installed capacity and the amount of electricity they generated in 2016. A third nuclear power plant, which is expected to begin operating before 2030, is under construction at the same location [33]. Rio de Janeiro state, however, does not have uranium reserves, which are located in the states of Bahia and Ceará [22]. Nuclear fuel for the power plants is partially produced in RJ state (the conversion step of the nuclear fuel cycle, in which uranium concentrate is dissolved, purified, and then converted to gas to be enriched, takes place abroad [34]).

Although sugarcane products (bagasse and molasse/juice) are important energy sources for Brazil, accounting for 17.5% of the entire internal energy supply in 2016 [35], they are not a significant source for the RJ state energy system. These energy sources originate from agriculture production, either directly or as residuals, which in RJ state account for less than 1% of economic production. Nevertheless, in 2016, one power plant in the state used sugarcane bagasse as fuel to generate electricity (see Table 1). In addition, four distillery plants in the state produced 95,000 cubic meters of ethanol in 2016. This production, however, was not enough to fulfill the state transportation sector's ethanol demand, resulting in 1.1 million cubic meters of ethanol imported from other Brazilian states in 2016.

As seen in Figure 1, renewables' participation in energy and electricity supply in RJ in 2016 was not significant (6.2% and 9.5%, respectively), whereas in Brazil, these values were 44% and 82% [35]. Table 2 compares renewable electricity generation's installed capacity between RJ state and Brazil. Unlike in other areas of the country, RJ state's renewable potential is not substantial. For instance, hydropower generation competes with water supply in the state [22], and wind and solar potential is more abundant in other areas of the country [36], thus contributing to lower development of these sources in RJ. The exception is rooftop solar photovoltaic generation, which has potential to grow in RJ state in the coming years [36].

Table 2. Renewable electricity generation's installed capacity: RJ state and Brazil—2016. Source: [22,35].

Source	RJ State (MW)	Percentage of RJ's Total	Brazil (MW)	Percentage of Brazil's Total
Hydropower	1184	14.1	96,925	64.4
Wind onshore	28.1	0.3	10,124	6.7
Utility solar PV	-	-	24.0	0.02
Rooftop solar PV	5.05	0.1	56.9	0.04
Hydropower	1184	14.1	96,925	64.4
Wind onshore	28.1	0.3	10,124	6.7
Utility solar PV	-	-	24.0	0.02

The installed capacity detailed here, however, is not sufficient to satisfy the state's electricity demand. In 2016, almost half of the electricity supplied in RJ state was imported from other Brazilian states. Brazil's National Interconnected Electricity Transmission System (SIN), which ran through 124,000 km and connected almost 99% of the country in 2016 [37], provided the remaining electricity needed by consumers in RJ state.

1.2. Light-Duty Passenger Vehicle Transportation Sector

Given the purpose of this paper, it is also necessary to map RJ state's transportation sector, in particular the light-duty passenger vehicle segment. This sector is relevant for transportation in RJ, being responsible for 78% of passenger kilometers (pkm) performed in the state's passenger transportation sector [22–24]. Although it would be interesting to analyze the substitution and complementarity effects between public and private passenger transportation in the presence of emission reduction policies, such analysis is outside the scope of this study, and will be the focus of future work.

As of 2016, the light-duty passenger vehicle fleet in RJ state was around 3.4 million vehicles [28]—for comparison, around 22,000 buses performed pkm in the state, which emphasizes the weight of light-duty vehicle passenger transportation in RJ. Figure 2 shows fleet composition by engine technology. RJ state follows the national trend of greater participation of flex-fuel vehicles in the fleet. This type of vehicle, whose engine consumes either gasoline or ethanol, was first introduced in the country in 2003. Thirteen years later, flex-fuel vehicles accounted for 70% of the national light-duty passenger fleet [38]. The participation of pure ethanol vehicles in the state fleet, however, is much smaller. These vehicles are old units from the 1980s that are still in circulation today (Brazil underwent a great development of ethanol cars during the 1970s and 1980s because of the increase in oil prices experienced at that time. During the 1990s, however, incentives and programs for the development of ethanol vehicles were discontinued. For more details, see: [39]). Diesel light-duty vehicles are not common in either Brazil or RJ state.

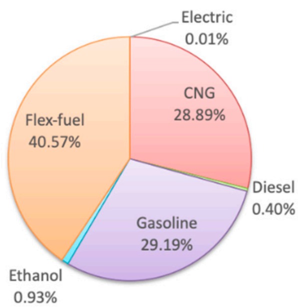


Figure 2. Light-duty passenger vehicles in Rio de Janeiro (RJ) state by engine technology—2016. Source: [28].

CNG vehicles' share in the state fleet is also significant. These units are mostly used by taxi companies due to lower CNG prices. In addition, CNG fueling infrastructure is developed in RJ state, which is not common elsewhere in the country (except in São Paulo state and other demographically dense areas). These factors thus contribute to greater participation of CNG vehicles in the state fleet.

In 2016, there were only 365 electric vehicles in RJ state (of which 89% were hybrids, 5% were plug-in hybrid vehicles (PHEV), and 6% were battery electric vehicles (BEV)). Overall, there were around 3600 electric vehicles in Brazil in that year. EVs are costly in Brazil due to taxes and the exchange rate (all available models in Brazil are imported). In the past few years, however, some incentives and subsidies to stimulate EV adoption have been implemented and have contributed to a decrease in EV costs in the country [40]. As a result, sales of EVs in Brazil have increased 992% in the 2016–2019 period [38].

The information detailed here was used to model RJ state's reference energy system (RES), which depicts the baseline scenario in the energy systems model that will be described in the following section.

2. Materials and Methods

This study analyzes how to implement climate change mitigation policies to reduce emissions in the transportation sector in RJ during the 2016–2050 period. We use an energy systems model (OSeMOSYS) to find the best way to fulfill RJ state's energy and transportation demands at the lowest possible cost. OSeMOSYS uses linear programming to minimize overall energy system discounted costs given capacity and technological constraints.

The model is represented by technologies that both produce and use energy carriers (fuels). Moreover, all technologies in RJ state have operating and investment costs associated with them in each year modeled. The goal of OSeMOSYS is to best allocate the use of these technologies, given their costs and technical characteristics, to fulfill exogenously determined electricity and transportation demands.

Figure 3 portrays RJ state's reference energy system (RES). This is a representation of the state's energy sector as of 2016. As a representation of reality, OSeMOSYS models the energy system from resource extraction, passing through its transformation into energy carriers by several energy technologies, until final consumption by agents in the economy. Demand growth and system expansion up to 2050 follow current projections and plans already announced by the government, such as the National Energy Plan 2050 (PNE 2050) [41].

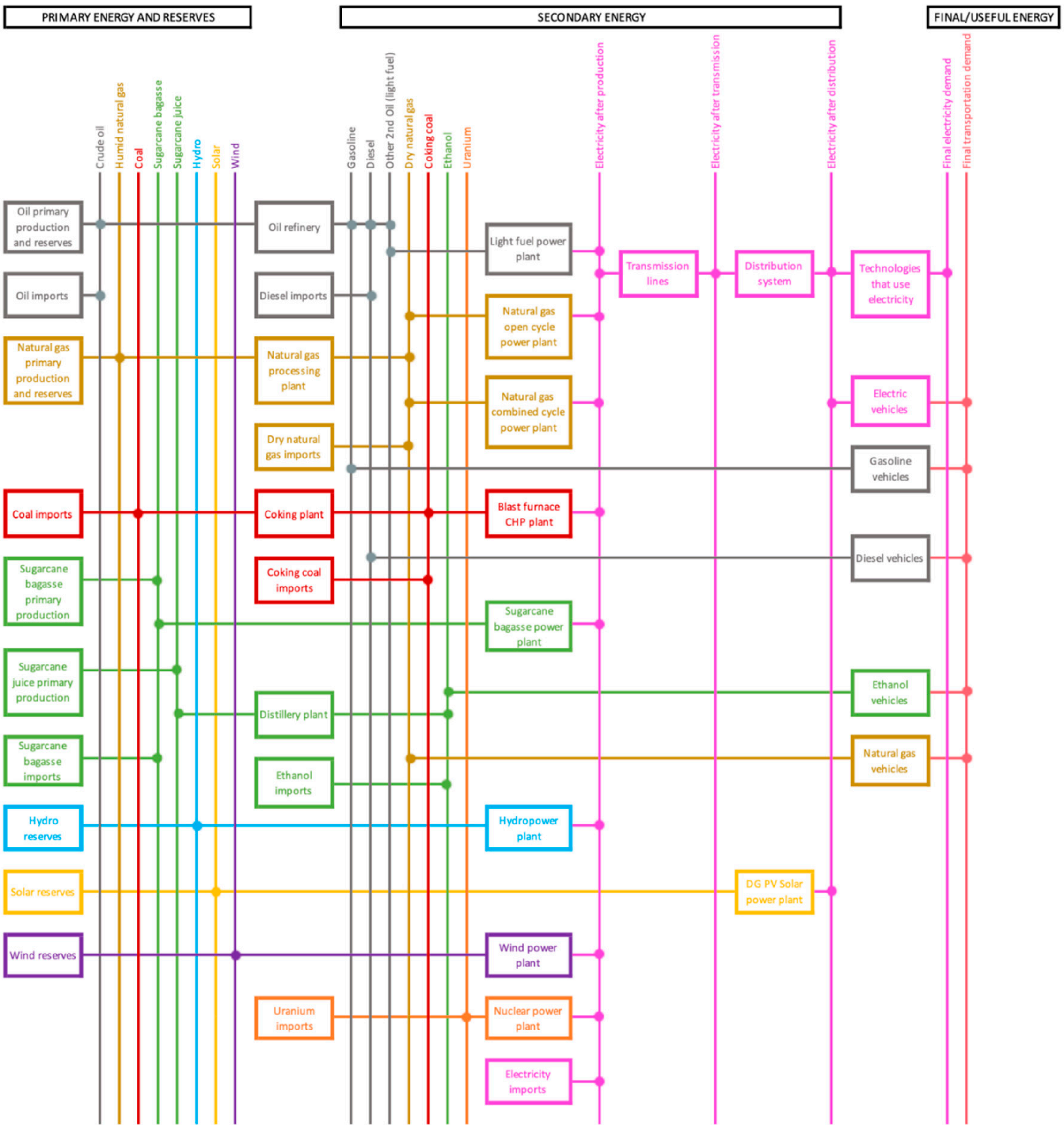


Figure 3. Rio de Janeiro state's reference energy system (RES).

As mentioned, the model's components are technologies and fuels. Fuels are energy carriers such as automotive gasoline, electricity, or crude oil, and are represented by vertical lines in Figure 3. Technologies transform or produce fuels, denoted by boxes in the figure. Boxes also represent imports of fuels into the system. For instance, primary energy and its associated reserves (such as oil) are explored by an Oil production technology, thus producing the fuel Crude oil, which is refined in the Oil refinery technology to produce the fuels Gasoline, Diesel, and Light fuel oil. These, in turn, are used by Power plants and vehicle technologies (Gasoline and Diesel vehicles). The fuel Electricity produced in power plants is sent to final consumption through Transmission and Distribution lines, while vehicle technologies fulfill the transportation demand in passenger kilometers (pkm).

Table 3 lists the installed capacity for the technologies shown in Figure 3 in the reference year (2016). The fossil fuels extracted in RJ are oil and natural gas. Their reserves are represented as an upper limit to the fossil fuel primary production technology, and thus do not need to be modeled separately [42]. The oil extracted in the state is transformed into diesel, gasoline, and light fuel oil in refineries, while humid natural gas extracted in RJ is transformed into dry natural gas in processing plants. Local production, however, is not sufficient to fulfill the internal demand. As a result, oil, dry natural gas, and also some diesels have to be imported from abroad. In RJ, fossil fuels are used in power plants (light fuel oil and natural gas), and to fuel vehicle technologies (gasoline, diesel, and natural gas vehicles).

As explained in Section 1.1, all coal used as an energy source in RJ is imported from other Brazilian states and is transformed in coking plants. Coking coal is also imported from abroad and other Brazilian states. In this model, coking coal is used in a blast furnace combined heat and power plant located in a steel mill.

RJ also explores renewable resources, which are limited by factors such as area, resource availability, and so on. For instance, for hydroenergy, reserves were calculated according to the potential to generate power given the state rivers' natural energy inflow by season. Solar reserves, in turn, considered only the rooftop solar (distributed generation (DG)) potential. Wind reserves were also calculated according to the power generation potential, which accounts not only for wind speed and other technical characteristics but also for available area for production. For sugarcane products (bagasse and juice), production limitation is represented not only by area planted but also by the harvest season, which in RJ state takes place from April to November [43].

Renewables in RJ are mostly used for electricity generation, with the exception of sugarcane juice, which is transformed into ethanol in distillery plants. Ethanol produced and imported from other Brazilian states is used in ethanol cars.

Besides renewable power plants (hydro, sugarcane bagasse, wind, and distributed generation solar photovoltaic), electricity in RJ is also generated in nuclear power plants. Although the manufacture of nuclear fuel used by Brazilian nuclear power plants partially takes place abroad, it was considered an import in the model for simplification purposes.

In-state electricity production, however, is not sufficient to satisfy the internal demand. Therefore, electricity is imported from other Brazilian states through transmission lines. Finally, electricity is distributed for final consumption through the distribution system to be used in electric vehicles and other technologies (light bulbs, air conditioners, household appliances such as electric showers, microwaves, etc.).

The technologies detailed here are characterized by parameters. Such parameters are used to describe each technology's technical characteristics and cost of use. This way, the model may closely reflect the energy system of RJ state in 2016 and can be utilized to analyze how the energy system will respond to various climate change mitigation policies. Cost parameters pertain to the costs to install new technology capacity (capital cost), to operate and maintain existing technology capacity (fixed cost), and to generate activity (fuel) within a technology to satisfy demand by end uses or other technologies (variable cost). Inclusion of these parameters will allow the model to choose the overall lowest-cost technologies to fulfill electricity and transportation demands. Data sources for cost parameters are listed in Appendix (Table A1).

The technical parameters that characterize the technologies in RJ's RES are related to their performance. Transformation facilities (refineries, for instance) and power plants have different fuel conversion efficiency levels. Vehicle technologies also present different levels of fuel efficiency per passenger kilometers (pkm) generated. Such efficiencies are detailed in Appendix A (Table A1). Some technologies, such as power plants and vehicles, thus also compete to satisfy demand on how efficiently they can produce activity (electricity and passenger kilometers). Other technical parameters used to characterize technologies are their operational life, residual capacity (from before the model period), capacity factor, emission per unit of activity, and emissions penalty, when applicable.

To fully characterize the RES of RJ state, it is also necessary to detail parameters related to exogenous electricity and transportation demand. Transportation demand in giga passenger kilometers

(Gpkm) is met at any time, each year. For electricity, it is possible to account for seasonal and daily variations in demand in *time slices*. For instance, electricity demand in RJ state varies according to *Seasons* (*Summer* and *Winter*) and different times of the day (*Daily Time Brackets*: in this model, they will be *Day*, *Night*, and *Peak* times). Table 4 presents the time slices used in the model.

Table 3. Capacity of technologies in RJ state's RES in 2016.

Technology	Capacity in 2016	Unit	Source
Primary production and reserves			
Oil primary production and reserves	438 [Reserves: 110,000]	PJ	[22]
Natural gas primary production and reserves	387 [Reserves: 16,500]	PJ	[22]
Sugarcane bagasse primary production	8.3	PJ	[22]
Sugarcane juice primary production	1.9	PJ	[22]
Hydro reserves	34	PJ	[44]
Solar reserves	85	PJ	[36]
Wind reserves	32	PJ	[36]
Imports			
Oil imports	132	PJ	[22]
Coal imports	110	PJ	[22]
Sugarcane bagasse imports	0.004	PJ	[22]
Diesel imports	2	PJ	[22]
Dry natural gas imports	12	PJ	[22]
Coking coal imports	33	PJ	[22]
Ethanol imports	24.4	PJ	[22]
Uranium imports	198	PJ	[22]
Electricity imports	92	PJ	[22]
Transformation plants			
Oil refinery	578	PJ	[22]
Natural gas processing plant	282	PJ	[22]
Coking plant	46	PJ	[45]
Distillery plant	8.4	PJ	[22]
Power plants [1]			
Light fuel oil power plant	0.49	GW	[46]
Natural gas open-cycle power plant	3.3	GW	[46]
Natural gas combined-cycle power plant	1.2	GW	[46]
Blast furnace combined heat and power (CHP) plant	0.021	GW	[46]
Sugarcane bagasse power plant	0.049	GW	[46]
Hydropower plant	1.184	GW	[46]
Wind power plant	0.028	GW	[46]
Distributed generation photovoltaic (DGPV) solar power plant	0.005	GW	[47]
Nuclear power plant	2.0	GW	[46]
Electricity transmission and distribution (T&D)			
Transmission lines	-	-	-
Distribution system	-	-	-
Vehicle technologies			
Electric vehicles	0.004	Million cars	[28]
Gasoline vehicles	1.54	Million cars	[28]
Diesel vehicles	0.01	Million cars	[28]
Ethanol vehicles	0.86	Million cars	[28]
Natural gas vehicles	0.98	Million cars	[28]
Other technologies			
Technologies that use electricity	55	GW	[25,48,49]

[1] Diesel power plants in RJ state are used as energy generators for self-consumption and therefore are not available to be dispatched by a central planner. Hence, inclusion of these technologies in the model could bias the results.

Table 4. Time slices used in the model.

	Seasons	
Daily Time Brackets	**Summer: Oct–March**	**Winter: Apr–Sep**
Day: 06:00–17:00	Summer Day	Winter Day
Peak: 17:00–21:00	Summer Peak	Winter Peak
Night: 21:00–06:00	Summer Night	Winter Night

Moreover, some technologies may be employed for more than one purpose. For instance, a hydropower dam may be used to generate electricity and/or to store energy. In this model, however, for simplification purposes, technologies will operate in only one mode. In the example of a hydropower plant, it will only generate electricity.

2.1. Model's Algebraic Formulation

This section summarizes the equations of the model that minimize the costs to operate and expand RJ's energy system to fulfill final transportation and electricity demands until 2050. Once we have a model that is calibrated to reproduce the RES of RJ, different scenarios of climate change mitigation policy in the transportation sector are analyzed in the results section.

The model's objective is to minimize the total discounted cost of using technologies (*t*) employed in RJ, throughout the model's time horizon in years (*y*), so that exogenous fuel demands are met—electricity (in PJ) and transportation (in Gpkm). Total discounted cost is the sum of technologies' discounted capital, fixed and variable costs, as well as emissions (*e*) cost per technology, when applicable (i.e., when a penalty on emissions is applied) (Equation (1)). Technologies (*t*) are a function of their capacity factor (*c*), fuel conversion efficiency (ε), operational life (*yy*), and emissions (*e*). To ensure that exogenous demands are met, the model must observe the constraint in Equation (2): both final and intermediate technology fuel demands in each time slice (*l*) have to be lower than the fuel supply produced by technologies' total capacity (which multiplies a factor κ that converts capacity in GW or million cars to activity in PJ or Gpkm). Such capacity may either already exist from before the modeling period or be installed in each year, as needed. For further information on all the equations used, refer to OSeMOSYS documentation [42,50,51].

$$\begin{aligned} Minimize \sum_y \quad & TotalDiscountedCost_y(t(c,\varepsilon,yy,e)) \\ & = \sum_y \Big[CapitalDiscountedCost_y(t(c,\varepsilon,yy,e)) \\ & + FixedDiscountedCost_y(t(c,\varepsilon,yy,e)) \\ & + VariableDiscountedCost_y(t(c,\varepsilon,yy,e)) \\ & + EmissionsDiscountedCost_y(t(c,\varepsilon,yy,e)) \Big] \end{aligned} \tag{1}$$

$$subject\ to:$$

$$FuelDemand_{y,t,l} \le FuelSupply_{y,t,l} \le TotalCapacity_{y,t,l}(t(c,\varepsilon,yy,e)) * \kappa, \ \forall\ y,\ t,\ l \tag{2}$$

2.2. Definition of Scenarios

Finally, Table 5 describes the scenarios developed to analyze different climate change mitigation policies in the transportation sector in RJ: uptake of LDEVs at different time frames, carbon pricing on both production and consumption of fossil fuels in the electricity and transportation sectors, or a combination of both policies.

In the RES scenario, besides modeling RJ state's energy system for 2016, demand growth and system expansion up to 2050 follow current projections and plans already announced by the government, such as LDEVs reaching cost parity with internal combustion engine (ICE) vehicles only in the year 2049. On the other hand, in the PNE Alt scenario, which is an alternative scenario in the National Energy

Plan (PNE), it was assumed that LDEVs will start to increase their numbers in the national fleet during the 2030s. For such a development to take place, legal arrangements and robust regulation, including a ban on ICE vehicles, consistent public policies, and significant financial incentives for the adoption of electromobility, as well as substantial private investments and radical cost reduction on licensing of new LDEVs, were assumed. As a result, LDEVs will reach cost parity with ICE vehicles in 2041. This way, when compared with the reference, the alternative scenario presents a dynamic of "creative destruction" that leads to ICE vehicles being progressively and steadily replaced by LDEVs [41].

Table 5. Description of scenarios developed in this study.

Scenario	Description
RES	Current policies scenario; EV adoption picks up only in 2049
RES + CO_2 price	RES + carbon pricing
PNE Alt	Alternative official policy scenario in which EV adoption picks up in 2041
PNE Alt + CO_2 price	PNE Alt + carbon pricing
EV 2035	EV adoption picks up in 2035
EV 2035 + CO_2 price	EV 2035 + carbon pricing
EV 2030	EV adoption picks up in 2030
EV 2030 + CO_2 price	EV 2030 + carbon pricing
EV 2025	EV adoption picks up in 2025
EV 2025 + CO_2 price	EV 2025 + carbon pricing

Note: In scenarios with CO_2 price, the price varies as follows: USD 40/ton from 2017 until 2020, USD 60/ton until 2025, USD 80/ton until 2030, and USD 100/ton from then on.

In addition to the two official planning scenarios considered by the Brazilian government, we built scenarios in which LDEVs adoption happens sooner. In the EV 2025 and EV 2030 scenarios, we consider Bloomberg New Energy Finance's (BNEF) EV Outlook in which cost parity between ICE vehicles and LDEVs happens in the middle and end of the current decade [52]. In its projections, BNEF takes into account several policies (other than carbon prices) that are already implemented or will be in different regions of the world, such as European vehicle CO_2 regulations and China's LDEVs credit system [53]. These policies combine to make these two regions the fastest adopters of LDEVs in the world. Moreover, the outlook only considers policies that are credible to be enforced. By including these scenarios in our analysis, we assume that Brazilian and RJ state policies become more aggressive and in line with adoption policies from the most-developed LDEVs markets; as a result, LDEVs will reach cost parity with ICE vehicles in the year 2025 or 2030. For completeness, and to have a scenario in which cost parity happens at an intermediate point, we included the EV 2035 scenario in the analysis as well.

Moreover, the aforementioned scenarios were estimated with a CO_2 price, which considers a penalty per ton of CO_2 emissions starting at USD 40 in 2017 and gradually growing to USD 100 in 2050, based on recommendations from Stiglitz and Stern [54]. The carbon price applies to both the production and consumption of fossil fuels in the electricity and transportation sectors. We chose to analyze scenarios with carbon pricing because it is a usual mechanism to induce economic agents to internalize externalities [55]. Nevertheless, although it is the least distortionary method to induce agents to internalize the negative externality of pollution, carbon pricing has some shortcomings. Grainger and Kolstad [56] found that carbon taxes are probably regressive by focusing on the consumer side of such taxes, because lower-income individuals spend a larger share of their expenditures on energy consumption. They also noted that this regressivity can be mitigated through revenue-recycling schemes to rebate the potentially substantial tax receipts from the carbon tax. Other papers also highlighted the benefits once the production side is taken into account, for example, Dissou and Siddiqui [57] and Goulder et al. [58]. Marron and Toder [59] argued that carbon taxes can be extremely helpful in curbing GHG emissions, but substantial public finance hurdles need to be overcome when designing such a tax: setting the tax rate, collecting the tax, and using the resulting revenue.

They studied how to design such a carbon tax, as did Stiglitz [60]. Despite these obstacles, a price on carbon directs the cost to the root of pollution [61].

The carbon pricing estimated by Stiglitz and Stern [54] is in line with reaching Paris Agreement temperature targets. These values are much higher than those experienced in real carbon markets. In the European Union, for instance, the average Emissions Trading System (ETS) carbon market price gravitated around EUR 25 in 2019—a value similar to 2008 levels and the highest achieved since the economic crisis of that year [62]. During the COVID-19 pandemic, the ETS carbon price had fallen at first but recovered when the EU recovery plan, which includes several policies to foster decarbonization, was announced and approved. In fact, several sources have indicated it is important not to miss this economic recovery opportunity and keep fostering carbon pricing policies [63–65]. The ETS carbon market seems to be listening and behaving accordingly [62].

3. Results

The first step is to calibrate the model for the base year, 2016. Table 6 shows the calibration results for electricity produced by power plants. The model closely reproduces electricity generation in RJ state. Moreover, given that RJ state is part of the National Interconnected Electricity Transmission System (SIN), although the state needs to import electricity at some time during the year to supply the internal demand, a portion of in-state production is exported to other regions through SIN, thus partially explaining the difference seen in the calibration of electricity imports. For instance, in 2016, the total amount of electricity available for consumption (generation plus imports) was 56 TWh, whereas the electricity load (real-time demand plus losses) was 46 TWh.

Table 6. Calibration results for base year (2016).

Electricity Source [1]	Real Amount Generated (TWh)	Amount Generated in the Model (TWh)	Error (%)
Hydropower	5	5	0%
Wind onshore	0.07	0.07	0%
Natural gas	6.7	6.7	0%
Nuclear	13.4	13.4	0%
Light fuel oil	0.6	0.6	0%
Sugarcane bagasse	0.1	0.1	0%
Imports	25.51	23.12	−9%

[1] Solar PV and the CHP plant were not used in the calibration.

Table 7 reports the optimization results, which indicate that the most effective policy to curb carbon emissions is carbon pricing: compared with scenarios that only consider LDEVs adoption, emissions fall by 47% when a CO_2 price is implemented. Earlier LDEVs uptake (2025, 2030, or 2035) in the presence of carbon pricing slightly reduces emissions by 0.004% compared with LDEVs adoption taking place in either 2041 or 2049 (PNE Alt and RES scenarios, respectively). On the other hand, increased EV uptake without a carbon price does not have any effect on overall emissions since the energy system must generate additional electricity demanded by this growing number of EVs. Given the limitations on renewable energy generation in RJ state, this extra demand is supplied by fossil fuel sources.

Implementation of carbon pricing, however, is costly. For a given year of EV uptake, the overall costs in the presence of a carbon price are substantially higher. For instance, take the two scenarios in which EVs are adopted in 2025: with carbon pricing, the overall energy system costs are 308% higher. This value declines when EVs are adopted at later dates, down to 256% when adopted in 2049 (RES scenario).

Nevertheless, whether or not carbon pricing is implemented, the earlier EVs are adopted, the lower the overall costs will be to operate the energy system, despite the increased EV electricity demand. In scenarios without a CO_2 price, when EVs are adopted in 2025, 2030, 2035, or 2041, overall system costs vary from 18% to 4% lower when compared with the reference scenario, as seen in Figure 4. Figure 4 also shows that for scenarios with a CO_2 price, EV uptake in those years results in costs that are from 6% to 1% lower than in the reference scenario. This result is due to EVs' lower operation and maintenance costs, which are around 2% of capital costs per year for ICE and diesel vehicles [66], and around 1.4% for EVs [67].

Table 7. Optimization results—overall costs, emissions, and electricity generation for the 2016–2050 period.

Scenario	Overall Cost (Million USD)	Overall CO_2 Emissions (Mton)	Overall Electricity Generated (TWh)
EV 2025	327,864	100	3077
EV 2030	347,066	100	3008
EV 2035	361,841	100	2996
PNE Alt	381,829	100	2987
RES	399,817	100	2985
EV 2025 + CO_2 price	1,338,290	52.593	3140
EV 2030 + CO_2 price	1,362,468	52.593	3112
EV 2035 + CO_2 price	1,377,064	52.593	3102
PNE Alt + CO_2 price	1,401,775	52.595	3098
RES + CO_2 price	1,422,531	52.595	3096

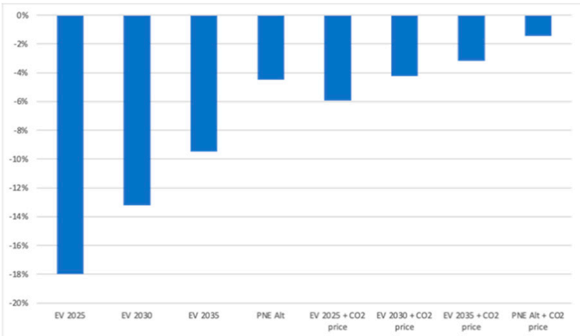


Figure 4. Percentage variation in overall energy system costs for different time frames of EV adoption—comparison with reference scenarios (with and without a CO_2 price).

Moreover, as expected, more EVs lead to greater electricity demand and, therefore, generation. Compared with the reference scenario in the absence of carbon pricing, when EV adoption picks up in 2025, 2030, 2035, and 2041, additional electricity ranging from 3% to 0.1% will be required to fulfill EVs' demands (Figure 5). In the scenarios with carbon pricing, when compared with the reference, additional electricity demand from EVs varies from 1.4% in the 2025 scenario to 0.1% in the PNE Alt (2041) scenario (Figure 5). The scenarios with carbon pricing require more electricity than those without it because fossil fuel plants with higher efficiency are retired.

Figure 6 shows the light-duty vehicle fleet composition for the reference, EV 2030, and EV 2025 scenarios in the years 2020, 2030, 2040, and 2050, with and without carbon pricing. Even before acquisition cost parity is reached with ICE vehicles, EV adoption starts to pick up as soon as vehicles reach the end of their operational life (which in Brazil is nine years, on average [68]). EVs are more fuel-efficient and have lower lifetime costs, thus attracting new consumers. In this model, however, there are no barriers to access charging infrastructure, which, in real life, affects consumer choice toward EVs. Other factors that influence vehicle purchase decision, such as access to parking, are not present either. In sum, vehicle acquisition choice is purely based on lifetime monetary costs. When a CO_2 price is applied, which further increases the cost of having an ICE vehicle further, EV adoption happens even sooner.

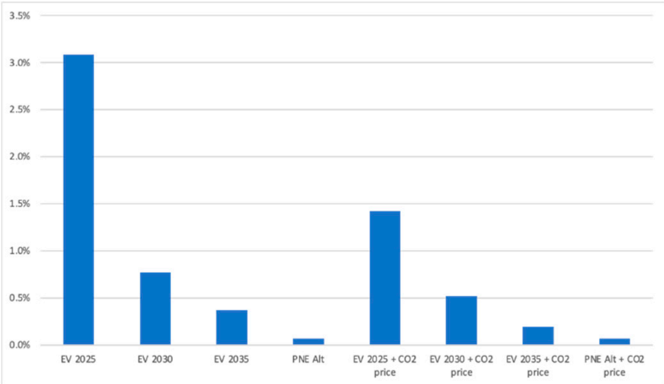


Figure 5. Additional overall electricity demand for different time frames of EV adoption—comparison with reference scenarios (with and without a CO_2 price).

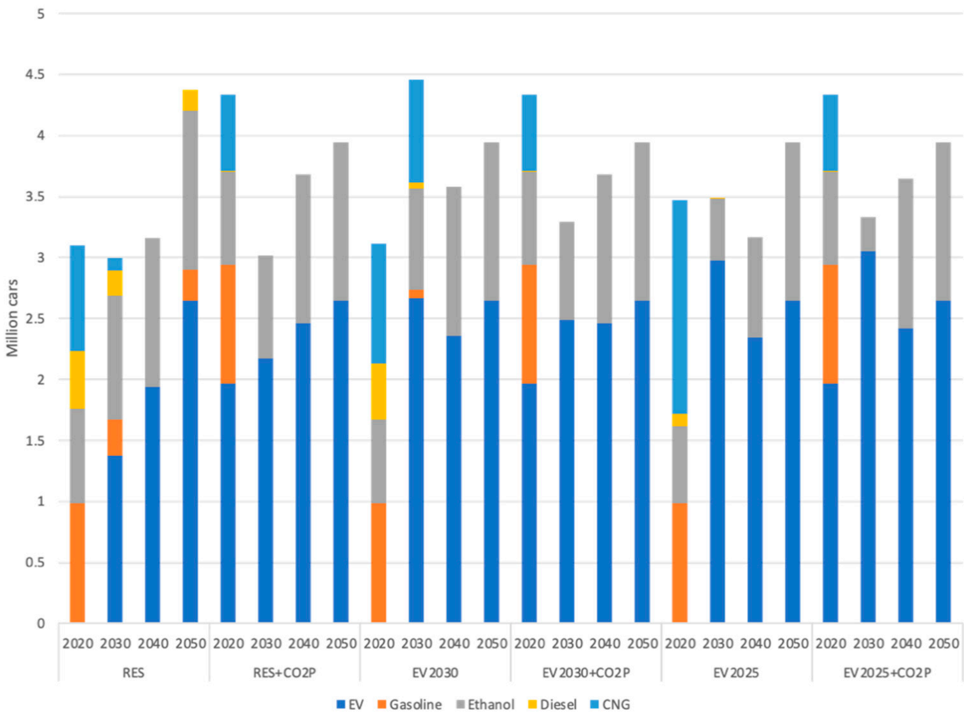


Figure 6. Light-duty vehicle fleet composition (million cars) by scenario and year.

Figure 6 also shows that in the years when cost parity with ICE is reached (e.g., year 2030, EV 2030 scenario), there is a jump in EVs uptake due to their higher efficiency, which can provide more pkm per unit of energy consumed per vehicle. After that, the fleet gradually adjusts. Since the model minimizes the system cost throughout the period, such an increase in technology adoption in a specific year is justified by the cost saving that will be accrued during the model's time horizon. In addition, although transportation demand grows during the 2016–2050 period, as explained in Section 2, because EVs are able to transport more passengers per unit of energy consumed, fewer vehicles overall will be necessary to fulfill the demand when more EVs are adopted.

Figure 6 also displays the participation of other vehicle technologies in the fleet during the period studied. Excluding the RES scenario, the vehicle fleet in 2050 is composed of EV and ethanol vehicles, in scenarios with and without carbon pricing. Ethanol vehicles, which include a fraction of flex-fuel vehicles (see Table 3), have higher efficiency in Gpkm/PJ than the other automotive technologies, thus explaining this result. Diesel, gasoline, and natural gas light-duty vehicles gradually lose their participation in the fleet due to their lower efficiency in Gpkm/PJ and higher costs, particularly in carbon pricing scenarios.

We also analyze scenarios in which there are no fossil fuel power plants in RJ state. All electricity is provided by renewables and imports. Given the state's limited renewable production capacity, as detailed in Section 1.1, fewer EVs are adopted because there is not enough electricity to supply both power and transportation demands. Table 8 compares the overall EV fleet composition for scenarios with and without fossil fuel power plants. In the scenarios that do not have carbon pricing—RES and EV 2025—26% and 10% fewer EVs are adopted overall in the period, while in the scenarios with a CO_2 price, EV uptake is 11% and 8% lower, respectively.

Table 8. Overall EV fleet composition (million cars) in scenarios with and without fossil fuel power plants.

Scenario	EVs (Mcars)	EVs (Mcars), No Fossil Fuel Power Plants
RES	47	35
RES + CO_2 price	76	68
EV 2025	67	60
EV 2025 + CO_2 price	87	80

Figure 7 displays the participation of vehicle technologies in the fleet in 2050 for scenarios with (left panel) and without (right panel) fossil fuel power plants. Gasoline cars still account for 1.64 million units in the RES, RES + CO_2 price, and EV 2025 + CO_2 price scenarios in a world without fossil fuel power plants. Compared with gasoline vehicles' participation in the fleet in 2050 from the original scenarios, which was 0.26 million in the RES scenario and zero in all the others, this is a stark change. Another interesting result is CNG vehicles' participation in 2050 in the EV 2025 scenario without fossil fuel power plants—2.30 million vehicles. Again, this value was zero in a world with fossil fuel power plants. Diesel vehicles are also still part of the fleet, which was not verified previously. These results indicate that if RJ state seeks to implement carbon-neutral policies in the future, which aim to decarbonize not only electricity generation but also transportation, further development of renewables must take place. The state has potential to produce offshore wind and utility solar [36], although there are no current plans to develop these energy sources in the near future.

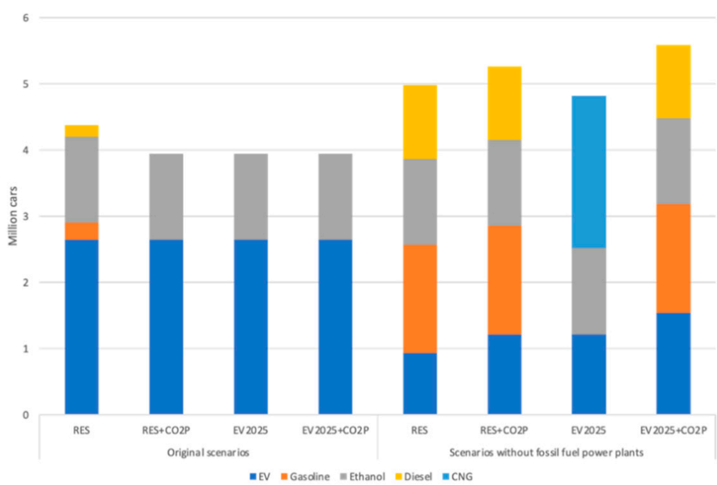


Figure 7. Light-duty vehicle fleet composition (million cars) in 2050—selected scenarios with and without fossil fuel power plants.

4. Discussion and Conclusions

In this paper, we use an energy systems model to indicate how electric vehicles can contribute to decrease emissions in the energy sector in Rio de Janeiro state, Brazil. A few conclusions arise: carbon pricing is the most effective way to decrease CO_2 emissions in an energy system that has serious limitations in renewable energy generation. When a carbon price is not present, EV adoption does not have an impact on reducing emissions because additional fossil fuel electricity must be generated to fulfill EVs' demand. This result, however, must be taken with a grain of salt. For instance, other renewable sources, such as offshore solar and wind and utility solar, were not considered in the model. RJ state has the potential to generate electricity from all these sources [36]. In addition, the state can increase biomass imports and invest in new biomass power plants. Expansion of nuclear power plants is also possible—although their higher capital costs and limited flexibility are issues to be considered when making investment decisions.

In fact, when fossil fuel power plants are excluded from the analysis, while renewable installed capacity remains unchanged, EV uptake is lower because not enough electricity is available to supply both transportation and final electricity demands. Therefore, to effectively decarbonize the transportation sector, decarbonization must first (or simultaneously) take place in the power sector—a result that corroborates the findings from Brozynski and Leibowicz [14].

When compared with just the adoption of EVs, although the implementation of a carbon tax contributed to boost the decarbonization of transportation, its effects may not be immediately felt in the transportation sector because of the technological lock-in and high reliance on liquid fuels [1]. Our model confirms this result: as Figure 6 shows, ICE vehicles start to be phased out when a carbon tax is implemented, but they are indeed retired when they reach the end of their operational life. In addition, Fridstrøm [69] reported that there is an "energy transition time lag" in transportation, in which new innovations may take between 5 and 25 years to spill over to the vehicle fleet. This lag, however, tends to decrease with the velocity of vehicle turnover—a result also confirmed by our model, where EVs start to replace ICE cars even before acquisition cost parity is reached.

From a policy perspective, however, carbon pricing is a tricky matter because its implementation is not easily accepted by the public—after all, it is a tax levied on energy consumption, which is an essential good for every household. Take as an example the *gilets jaunes* (yellow vests) protest movement in France, which started because of a planned increase in fuel prices caused by a carbon tax. Although economists consider carbon taxes to be the best climate change mitigation policy, their adoption and/or expansion is challenging, as detailed in previous studies [70]. Consumers are not keen on the idea of paying more taxes, especially in a developing country such as Brazil where income distribution is already very unequal. Thus, carbon pricing's distributional effects over society must also be considered. To address this distributional hurdle, carbon tax revenue can be returned to the taxpayers as a lump-sum payment such as tax cuts, thus ameliorating regressive taxation effects. Such a scheme has been in place in British Columbia, Canada, since 2008 [71]. Redistribution of carbon tax revenue to support poverty reduction and education, and to reduce other taxes, is a good alternative to increasing the carbon tax's public acceptance [70]. In addition, carbon tax revenue can be used to support future CO_2 reduction policies such as investment in renewables, low-carbon technologies and buildings, and energy transition infrastructure, such as electric vehicle charging stations.

In sum, a publicly acceptable carbon tax must be well designed to account for all the aforementioned issues, which hinder its implementation, particularly around election years. Therefore, although carbon pricing is the most efficient policy at hand to internalize the negative externality of fossil fuel consumption, it may not be the most effective one nowadays. On the other hand, establishing goals for clean transportation adoption sends market signals to manufacturers and consumers, who can, in turn, adjust their behavior in the best possible way. A policy that considers both approaches may be the best option at hand to decarbonize transportation.

Finally, our model considers how carbon pricing and a greater uptake of electric vehicles contribute to decreasing emissions in the road transportation sector in Rio de Janeiro. It does not, however, account for road passenger transportation technologies other than light-duty vehicles and also does not consider the role that mobility services such as carsharing, ride-hailing, and autonomous vehicles may have on road transportation emissions. An analysis that considers all road passenger transportation technologies and services and the substitution and complementarity effects among them in the presence of emission reduction policies (carbon taxes and others), as well as the economic impacts of such policies on society, are the focus of current and future work.

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Appendix A

Table A1. Data sources for the parameters used in the model.

Parameter	Source
Capital Cost [1]	[25,48,49,72–84]
Fixed Cost [1]	[33,66,67,72,74,75,79,80,82–89]
Variable Cost [1]	[37,72,75,90–96]
Capacity Factor For simplification, used only for variable renewable power plants - Hydropower plants: around 74% during the summer and 44% in the winter - Wind power plants: around 33% during the summer and 22% in the winter - Rooftop solar power plants: around 43% during summer days and 47% in winter days	[32,97–99]
Operational Life	[51,68,72,75,77,80,85,100–102]
Residual Capacity	See Table 3
Efficiency of Power Plants - Light fuel oil: 58% - Natural gas open cycle: 37% - Natural gas combined cycle: 58% - Blast furnace combined heat and power (CHP): 33% - Sugarcane bagasse: 36% - Nuclear: 36%	[22,24,28,37,72,85,103–106]
Efficiency of Vehicle Technologies - Electric vehicles (for simplification, electric vehicles were modeled as 100% electric). Efficiency: 1.36 Gpkm/PJ - Gasoline vehicles (flex-fuel vehicles were considered to be a fraction of either gasoline or ethanol vehicles, following directives detailed in [52]). Efficiency: 0.5 Gpkm/PJ - Ethanol vehicles: 0.55 Gpkm/PJ - Diesel vehicles: 0.32 Gpkm/PJ - Natural gas vehicles: 0.46 Gpkm/PJ	[28,106,107]

Table A1. *Cont.*

Parameter	Source
Efficiency of Transformation Plants and T&D	[22,37,74,108]
Emission per Unit of Activity	[109]
Emissions Penalty	[54]
Transportation Demand To calculate passenger kilometers of RJ state's vehicle fleet, the following steps were taken: 1. First, intensity of use of the vehicle fleet in km/year was calculated using estimations from [23], which considers how many kms, on average, vehicles drive, by type and age (age of vehicles in the RJ fleet comes from [28]); 2. This value was used to calculate average distance driven by the vehicle fleet, per vehicle technology; 3. Average distance per vehicle technology was then multiplied by vehicle occupation factor (from [24]) to find passenger kilometers per vehicle; 4. This value was multiplied by number of vehicles, by vehicle technology, and summed up for all technologies to find pkm for the entire vehicle fleet.	[23,24,28]
Electricity Demand	[37,97]

[1] All values were converted to 2016 USD.

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