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MECANISMOS DE COMPENSAÇÃO DE ENERGIA (NET-METERING) E SEUS EFEITOS NO CUSTO TOTAL DE PROPRIEDADE DE VEÍCULOS ELÉTRICOS

ENERGY COMPENSATION MECHANISMS (NET-METERING) AND THEIR EFFECTS IN THE TOTAL COST OF OWNERSHIP OF ELECTRIC VEHICLES

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Resumo - O mundo está caminhando para a transição energética e o transporte sustentável. Esta pesquisa abrange sistemas solares fotovoltaicos (PV) e veículos elétricos (EVs). O objetivo é avaliar os efeitos dos mecanismos de compensação de energia no custo total de propriedade (TCO) de EVs no contexto brasileiro. A metodologia emprega um modelo detalhado de TCO que considera biocombustíveis e subsídios para eletricidade. Os estudos de caso contemplam quatro níveis de veículos (entrada, compacto, médio e luxo) e quatro regras de net-metering (anterior, atual, considerada e futuro). Os resultados mostram as variações médias, mínimas e máximas nos custos de energia (EC), custos anuais (AC) e TCO de veículos de combustão interna (ICVs) e veículos elétricos a bateria (BEVs) para cada mecanismo de compensação. Os efeitos dos mecanismos de compensação são maiores no EC, seguido pelo AC e, então pelo TCO. Considerando todos os níveis e valores médios, a variação do TCO do cenário anterior para o atual é de 1,6%, do cenário anterior para o considerado é de 4,3% e do cenário anterior para o futuro é de 6,8%. Portanto, embora os efeitos dos mecanismos de compensação energética sejam mais significativos para EC e, em menor grau, para AC, no TCO não chegam a 7%.

Palavras-chave: Transição Energética. Sistema Fotovoltaico. Transporte Sustentável.

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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. Photovoltaic System. Sustainable Transport.

I. INTRODUCTION

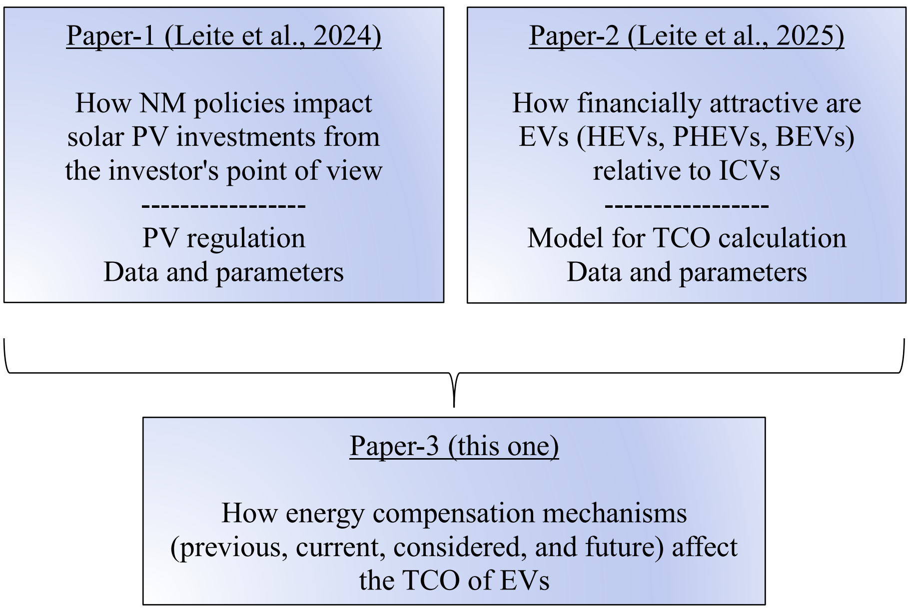
Climate change stands as one of the most important environmental challenges of the 21st century, driving the urgent need for an energy transition toward renewable and low-carbon sources. Solar energy, due to its abundance, plays a key role in this shift, enabling cleaner electricity and powering sustainable 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



Source: Authors, 2025.

II. METODOLOGY

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).

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

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].

2.1 – 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)	

III. RESULTS

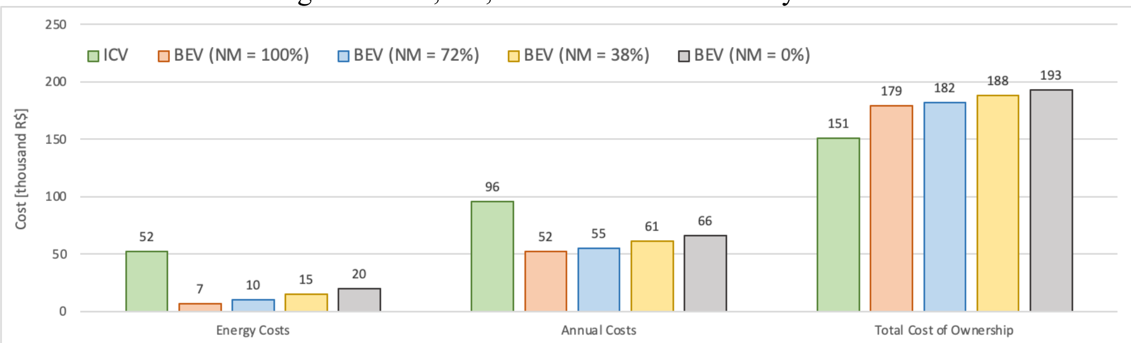
Tables 4-7 and Figures 2-5 present EC, AC, and TCO variations in % and values in thousand R$ for entry, compact, medium, and luxury levels; respectively. Considering all tables and figures, as explained in the previous paper, EC and AC of all vehicles are higher for ICVs than for BEVs (second column, 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) 100%	72%	38%	0%	Δ ICV → BEV (NM) 100%	Δ 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



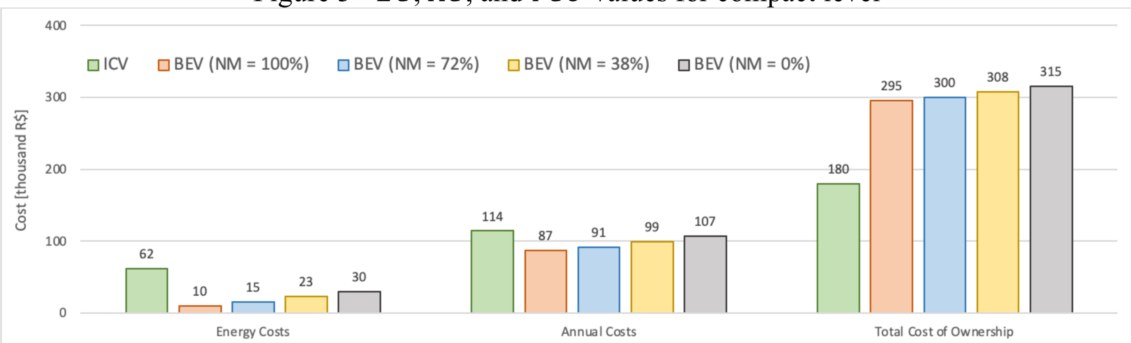
Source: Authors, 2025.

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) 100%	72%	38%	0%	Δ ICV → BEV (NM) 100%	Δ 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



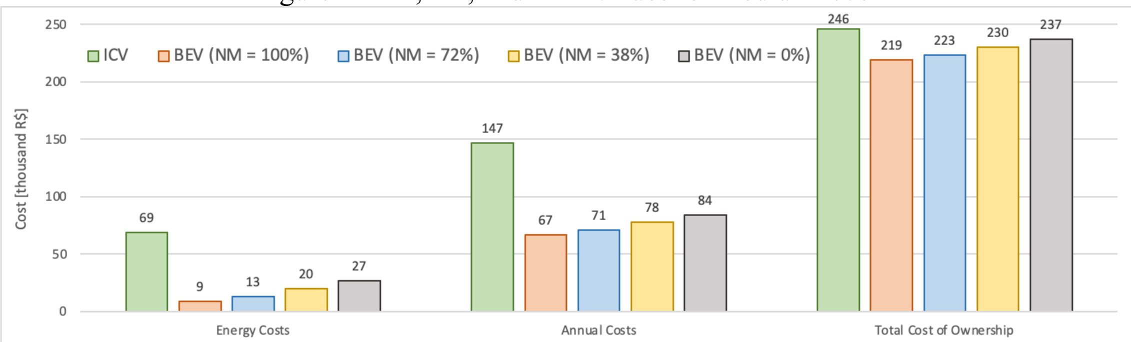
Source: Authors, 2025.

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) 100%	72%	38%	0%	Δ ICV → BEV (NM) 100%	Δ 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



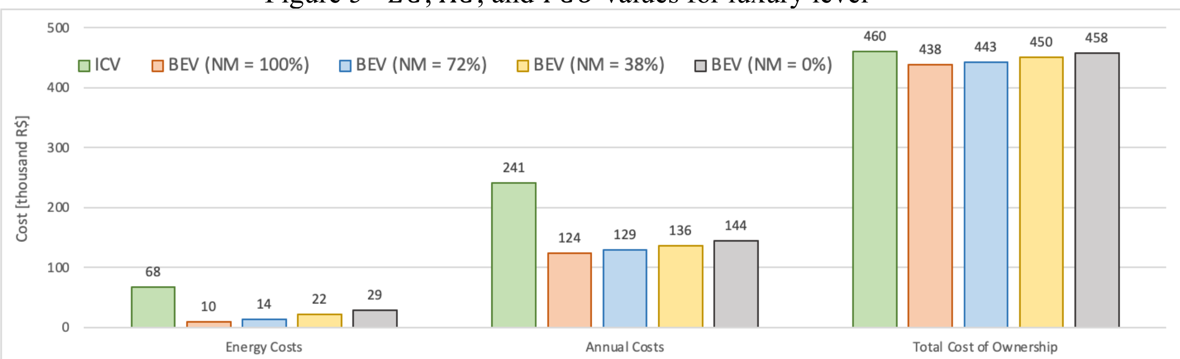
Source: Authors, 2025.

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).

Table 7 - EC, AC, and TCO variations for luxury level

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



Source: Authors, 2025.

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% →			Minimum and Maximum Values Δ BEV (NM) 100% →		
	72%	38%	0%	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%

IV. CONCLUSION

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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