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Research Article

Cost-benefit analysis for transitioning Thailand's passenger cars to electric drives

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Abstract: The transportation sector significantly contributes to global CO2 emissions, thereby there exists a requirement for the sustainable alternatives. The work compares the total cost of ownership (TCO) of sport utility vehicles with different powertrain technologies, including internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs), in the Thai market. Using a detailed TCO model, the study considers purchase price, depreciation, fuel/electricity costs, maintenance, insurance, annual tax, and government incentives. Data from literature and market reports assess the financial viability of each vehicle type, structured into four comparison groups based on model and popularity. Findings indicate that while ICEVs have lower initial costs, BEVs and HEVs achieve competitive TCO with subsidies and better battery technology. Results show significant energy and maintenance savings for EVs over their lifecycle compared to ICEVs. However, high initial costs and inadequate charging infrastructure hinder EV adoption in Thailand. The study concludes that targeted policies and incentives are essential to promote EV adoption, reduce emissions, and advance sustainable transportation. These insights guide consumers and policymakers in supporting Thailand's electric mobility transition.

Keywords: *Clean energy, Electrification, Electric vehicle, Policy recommendation, Total cost of ownership*

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Nomenclature	Abbreviations	Descriptions
	BEV	Battery Electric Vehicle
	CO_2	Carbon Dioxide
	EV	Electric Vehicle
	GHG	Greenhouse Gas
	HEV	Hybrid Electric Vehicle
	ICEV	Internal Combustion Engine Vehicle
	PHEV	Plug-in Hybrid Electric Vehicle
	SUV	Sport Utility Vehicle
	VAT	Value Added Tax
	TCO	Total Cost of Ownership

1. INTRODUCTION

Global warming, defined as the rise in the temperatures of earth surface and ocean, is primarily driven by human activities such as fossil fuel combustion, deforestation, and industrial processes. These activities lead to the accumulation of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), in the atmosphere. The increased concentration of GHGs traps heat through the greenhouse effect, causing a range of environmental impacts such as melting polar ice caps, rising sea levels, and more frequent and severe weather events. These changes disrupt ecosystems, reduce biodiversity, and impact agriculture, water resources, and human health, leading to economic losses and exacerbating social inequalities.

Like many countries, Thailand faces significant challenges in reducing its greenhouse gas emissions. According to a 2022 report on CO_2 emissions from energy use, the power generation and transport sectors are the most significant contributors, accounting for 35.49% and 32.12% of total emissions, respectively [1]. The transportation sector, dominated by internal combustion engine vehicles (ICEVs), not only emits CO_2 but also other harmful pollutants such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM). These pollutants deteriorate air quality and pose significant health risks, including respiratory and cardiovascular diseases.

Electric vehicles (EVs) offer a promising solution to reduce emissions from the transport sector. Extensive research has demonstrated the potential of EVs to mitigate energy consumption and CO_2 emissions [2,3]. Studies by Suttakul, et al. [4] and Janpoom, et al. [5] have investigated the factors influencing energy consumption and emissions of EVs and ICEVs under real-world driving conditions. These studies have shown that EVs, especially battery electric vehicles (BEVs), can significantly reduce emissions compared to traditional ICEVs. Additionally, policy recommendations have been proposed to promote EV adoption and infrastructure development, as highlighted in the works of Ayetor, et al. [6], Muangjai, et al. [7], Ghosh and Sarkar [8], and Achariyaviriya, et al. [9].

Rising fuel prices and environmental concerns have prompted manufacturers, consumers, and governments to prioritize energy-efficient and eco-friendly vehicles. This focus has spurred innovations leading to the development of three main types of commercial electric vehicles: Hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and BEVs. Despite their environmental benefits, the adoption of EVs in Thailand has been relatively slow. Significant barriers include high initial costs, concerns over battery lifespan and replacement expenses, limited driving range, and insufficient charging infrastructure [9]. EVs are a relatively new option for Thai consumers, who may have concerns about the reliability of new powertrain systems, the costs associated with battery replacement, the limited range of BEVs, and the overall value compared to ICEVs. Therefore, providing detailed and persuasive information about EVs is crucial to foster consumer interest and acceptance of this new technology. The Thai government has set ambitious targets to increase the market share of EVs, aiming for at least 69% of new vehicles to be electric by 2035. This objective is supported by policies that encourage the establishment of a domestic EV manufacturing industry and promote consumer purchases through subsidies, tax incentives, and investments in charging infrastructure [10].

The total cost of ownership (TCO) is a critical factor influencing consumer decisions between EVs and ICEVs. TCO encompasses all costs associated with purchasing and operating a vehicle over its lifetime, including depreciation, energy costs, maintenance, insurance, and taxes. Understanding TCO is essential for consumers to make informed decisions and for policymakers to design effective incentives. This study employs a detailed TCO model to compare the costs of owning sport utility vehicles (SUVs) with different powertrain technologies (ICEV, HEV, PHEV, and BEV) in the Thai market. The analysis considers various factors such as vehicle purchase price, fuel and electricity costs, maintenance expenses, insurance premiums, and government incentives. By focusing on SUVs, which are high-performance vehicles with a 5- to 7-seat configuration and a large body designed for diverse applications, the study provides a comprehensive cost comparison of HEV, PHEV, and BEV versus ICEV.

The TCO model has gained popularity among government and private agencies in many countries as a tool for evaluating the financial viability of different vehicle technologies. By incorporating various costs, the TCO model offers valuable insights into the long-term economic implications of vehicle ownership. The findings of this study offer significant insights for consumers, helping them understand the financial aspects of EV ownership and making it easier to compare with traditional ICEVs. Moreover, the study provides recommendations to enhance and promote the efficient and effective use of EVs in Thailand. By facilitating consumer decision-making and supporting policy development, this study aims to drive the adoption of EVs and contribute to reducing GHG emissions in the transport sector. This comprehensive approach not only benefits individual consumers but also supports broader environmental and economic goals.

2. LITERATURE REVIEWS

This study undertakes a comprehensive comparison of the costs associated with owning EVs and ICEVs to ascertain the more financially viable option. The analysis utilizes secondary data from various documents and articles, employing two primary techniques: The investment decision technique and the TCO technique.

2.1. Studies Using the Investment Decision Technique

Studies utilizing the investment decision technique vary in scope and assumptions, including vehicle type, travel distance, lifespan, and fuel price. Despite these variations, their conclusions often converge. For instance, Kongsakpaibul [11] and Thammasiri [12] concluded that EVs are not cost-effective due to high battery costs and prolonged payback periods, although the cost-effectiveness improves with increased travel distance and higher fuel prices. Aussawachattongchai [13] study on electric bicycles indicated lower costs and faster payback periods compared to conventional bicycles. Gonzalez-Salazar, et al. [14] employed net present value (NPV) analysis to assess the economic and environmental impacts of renting versus selling EV batteries, finding that battery purchase is more cost-effective for high-mileage drivers. Dimanchev, et al., [15] emphasized the necessity of expanding EV charging infrastructure to support BEV adoption, noting that insufficient infrastructure investment delays the widespread adoption of BEVs. Arowolo and Perez [16] demonstrated that integrating rooftop solar PV with EVs significantly reduces CO_2 emissions and offers a favorable NPV, showing a synergistic approach to decarbonizing both the transportation and power sectors.

2.2. Studies Using the Total Cost of Ownership (TCO) Technique

The TCO technique accounts for factors such as vehicle selection, usage duration, driving style, depreciation, interest rate, maintenance costs, and distance traveled. Methodological differences result in varying conclusions. For example, Bubeck, et al., [17] and Hagman, et al., [10] presented divergent results on the cost-effectiveness of EVs. Bubeck, et al., [17], excluding government subsidies, found current EVs economically disadvantageous. In contrast, Hagman, et al., [10], incorporating Sweden’s government subsidies, concluded that BEVs have a lower TCO compared to other vehicle types. Future projections by Bubeck, et al., [17] indicated that EVs will become more cost-effective as battery prices decrease and technology advances. A study by Suttakul, et al., [18], suggested that HEVs currently offer the best TCO, while BEVs could become cost-competitive with adequate subsidies.

Comparative studies across different countries reveal diverse impacts of electrification. Research in the UK, USA, and Japan from 1997 to 2015 showed significant cost reductions for EVs due to subsidies and market adaptations [19]. Scorrano, et al., [20] highlighted the importance of urban driving patterns and home charging infrastructure in Italy, finding that operational savings could offset higher upfront costs. In China, TCO studies predict that small BEVs will achieve cost parity by 2025, driven by technological advancements and policy incentives [21]. Ayetor, et al., [6] highlighted the potential of PHEVs to offer lower lifetime costs in Ghana, considering local energy policies and conditions.

The summary comparing costs between EVs and ICEV found that the factor affecting the cost-effectiveness is the purchasing price. This is the same factor as the study of consumer behavior in choosing EVs. The key variable that causes the TCO to decrease effectively is government measures, such as funds, benefits, and the development of related technology that will cause the price reductions of EVs and batteries, attracting more consumer needs.

Recent studies have also explored the influence of government incentives on TCO. For example, subsidies for EV purchases and investments in charging infrastructure have significantly reduced the TCO for consumers, making EVs more competitive with ICEVs. These incentives not only lower the upfront costs but also reduce operational expenses through cheaper energy costs and lower maintenance requirements. The primary factor influencing cost-effectiveness is the purchasing price. Government measures, such as subsidies, tax incentives, and technological developments, play a crucial role in reducing the TCO of EVs and increasing consumer adoption. For instance, the integration of advanced battery technologies and improvements in energy efficiency are expected to lower the TCO of EVs further, making them a more attractive option for consumers.

2.3. Unique Contributions of Present Work

This study uniquely applies the TCO technique to the Thai vehicle market, taking into account local data and market behaviors, including purchasing price, depreciation, energy cost, interest cost, insurance, maintenance, battery replacement, and tax costs. It evaluates TCO models for different vehicle brands and powertrains, assessing the impact of public and private support measures on BEV competitiveness. The study aims to identify strategies to make BEVs’ TCO competitive with ICEVs, encouraging the transition to EVs through appropriate policies and incentives.

Moreover, this study provides an in-depth analysis of specific factors influencing TCO in the Thai context, such as regional variations in energy costs and the impact of local government policies on vehicle depreciation rates. By comparing a wide range of vehicle models and considering both direct and indirect costs, this research offers a comprehensive perspective on the financial implications of EV ownership. The findings are intended to guide both consumers in making informed vehicle purchase decisions and policymakers in designing targeted incentives to promote EV adoption.

3. METHODOLOGY AND ASSUMPTIONS

Research on vehicle TCO revealed that both direct and indirect lifetime costs significantly influence TCO. These cost data were used to analyze the impacts of factors such as increased total kilometers driven and longer ownership durations.

3.1. Selection of Sample Vehicles

In this study, the sample selection focused on Sport Utility Vehicles (SUVs) due to their significant market presence in Thailand. As detailed in Table 1, SUVs not only accounted for the highest number of sold models in the market in 2023 but also offered the most extensive range of EV models. The analysis was structured into comparison groups based on vehicles that feature both ICEV and EV powertrains from the same brand and model [22], as follows:

> ***Group 1****: HEV vs. ICEV (Toyota Corolla Cross HEV Safety and Toyota Corolla Cross 1.8 Sport Plus)*
> ***Group 2****: PHEV vs. ICEV (MG HS PHEV X and MG HS TURBO X)*
> ***Group 3****: BEV vs. ICEV (MG ZS EV X and MG ZS 1.5 X)*
> ***Group 4****: BEV vs. HEV vs. ICEV (BYD Atto 3, Honda HR-V e:HEV EL, and Toyota Corolla Cross 1.8 Sport Plus)*

Note that Group 4 is the comparison between the best-selling SUV models in each powertrain category. However, PHEV is excluded from this group as it represented only 1.79% of new registrations in 2023, a minimal proportion when compared to other powertrains [23], as illustrated in Fig. 1. Technical details of the 8 model vehicles are provided in the Appendix.

Table 1. Classification of vehicle models by powertrain, officially sold in 2023.

Vehicle Class	ICEV	HEV	PHEV	BEV	Total Models
SUV	128	68	59	20	275
Sedan	79	38	18	22	157
MPV	47	49	0	6	102
Pickup Double Cab	101	0	0	0	101
Hatchback	63	2	2	15	82
Pickup Space Cab	72	0	0	0	72
Coupe	60	2	0	0	62
PPV	39	0	0	0	39
Pickup No Cab	36	0	0	1	37
Other	12	0	2	4	18
Sportback	11	2	0	2	15
Station Wagon	5	0	2	8	15
Avant	7	2	0	0	9
Convertible	6	0	0	0	6
Roadster	5	1	0	0	6
Cab & Chassis	3	0	0	0	3
Crossover Coupe	0	0	0	3	3
Passenger Van	3	0	0	0	3
Cabriolet	1	0	0	0	1
Truck Van	1	0	0	0	1

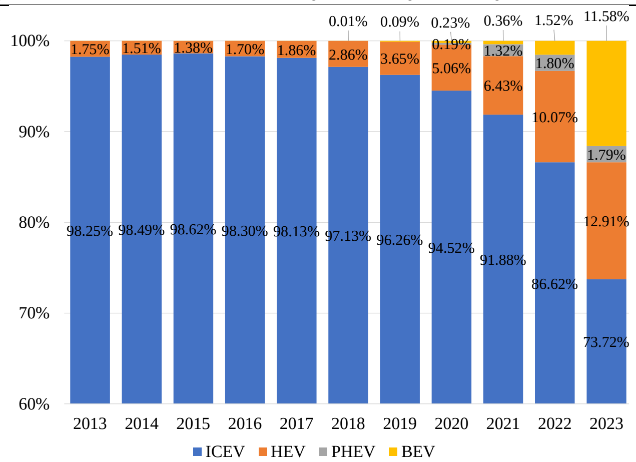


Figure 1. Proportion of new passenger vehicle registrations from 2013-2023, classified by powertrains.

3.2. Total Cost of Ownership Analysis for Vehicles

Generally, consumers are aware that opting for more expensive vehicles will result in higher long-term costs. However, the extent of these increased costs and their impact on decision-making remain unclear to most consumers. Cost estimation using the TCO model provides a comprehensive view of the expenses associated with vehicle ownership. The TCO approach is widely recognized for its ability to offer a holistic evaluation of both direct and indirect costs over the vehicle's lifecycle, thereby assisting consumers in making informed decisions.

In this work, the TCO was calculated by incorporating various cost components, including depreciation, energy, interest, insurance, maintenance, battery replacement, and annual tax. These cost factors are critical in understanding the true economic burden of owning a vehicle, as they capture the complete financial implications beyond the initial purchase price. The detailed breakdown of these costs is as follows:

$$TCO = D + E + I + IC + M + B + T \quad (1)$$

where, D represents depreciation cost, E is energy cost, I is interest cost, IC is insurance cost, M is maintenance cost, B is battery replacement cost, and T is annual tax cost. By integrating these elements, the TCO model offers a systematic and transparent approach for consumers to understand the financial implications of vehicle ownership, aiding in more informed decision-making.

3.2.1. Purchasing price

The purchasing price is a fundamental component in calculating the TCO for vehicles. In this study, the purchasing price refers to the retail price set by the vehicle manufacturer. This price serves as the initial investment and includes several critical cost components such as depreciation, interest cost, energy cost, maintenance cost, insurance cost, annual tax cost, and any applicable discounts. Incorporating these elements ensures a comprehensive and accurate assessment of the overall economic burden associated with vehicle ownership. By using the manufacturer's retail price, this study provides a standardized basis for comparing the financial viability of ICEVs and EVs within the Thai market. This comprehensive approach aligns with methodologies from various studies and industry practices, providing a robust framework for TCO analysis in automotive research. The purchase price of each vehicle is shown in the **Appendix.**

3.2.2. Depreciation

Depreciation cost refers to the reduction in the vehicle's value due to wear and tear over time. The depreciation rate varies by vehicle type and market popularity. Generally, smaller vehicles exhibit lower depreciation rates compared to larger ones, and vehicles that are more popular in the used market tend to depreciate less than those that are less popular. This study evaluates depreciation based on the 10-year salvage value subtracted from the retail price of each vehicle. The assumed salvage values for ICEVs, HEVs, PHEVs, and BEVs are 15%, 15%, 10%, and 8% of the initial purchase price, respectively [10,19,24]. The depreciation cost D can be calculated using the Sum-of-the-Years' Digits (SYD) method, as follows [25]:

$$D = \left((PP - RP) \times \frac{RL}{SYD} \right) \quad (2)$$

where PP represents the purchasing price, RP is the resale price, RL is the remaining years of useful life at the beginning of the year, and SYD is the sum of the digits from 1 to the estimated useful life.

3.2.3. Interest cost

In addition to purchasing vehicles outright with cash, consumers can finance their purchases through loans from banks or finance companies, commonly called hire purchases. This financing method allows consumers to avoid paying the entire cost upfront. Initially, the borrower is required to make a down payment, which is a percentage of the vehicle's purchase price. The remaining balance is then paid in installments over a specified period. Once all installments are paid, the finance company transfers vehicle ownership to the consumer.

Most hire purchase agreements utilize a flat interest rate, meaning the interest rate remains constant throughout the installment period. For instance, the interest rate for new vehicle hire purchases from the Siam Commercial Bank is currently 5.87% [26]. In this context, consumers making a 25% down payment on the purchase price and undertaking 48 monthly installments will have their interest costs I calculated as follows:

$$I = PP \times (100\% - DP) \times i \quad (3)$$

where PP is the purchasing price, DP is the down payment proportion, and i is the interest rate.

3.2.4. Energy cost

Different powertrain technologies utilize distinct types of energy. ICEVs rely solely on fuel, HEVs and plug-in hybrid electric vehicles (PHEVs) use a combination of fuel and electricity, while BEVs operate exclusively on electricity. The energy prices and fuel economy metrics used in this study are specified based on the context of Thailand, as follows: The fuel price is based on the retail price of Gasohol 91 in the Bangkok Metropolitan Area from 2004 to 2023 [27], with projections extending to 2038. According to the electricity tariffs of the Provincial Electricity Authority, Thailand, electricity prices in 2024 are derived from Schedule 1, applicable to residential type 1.1.2 users consuming over 150 kWh/month, with costs set at 4.4217 baht/kWh and a service charge of 38.22 baht/month [28].

Fuel economy reflects the energy cost incurred per distance traveled. Vehicles with higher fuel consumption result in greater energy costs. Utilizing data from the ECO sticker by the Office of Industrial Economics, Thailand, the energy costs from gasohol and electricity, defined as E_{gasohol} and $E_{\text{electricity}}$, respectively, can be calculated using the following equations:

$$E_{gasohol} = \frac{FE \times TKD \times FP}{100} \quad (4)$$

$$E_{electricity} = \left(\frac{EC \times TKD \times EP}{1000}\right) \quad (5)$$

where FE is the fuel economy, FC is the electric consumption, TKD is the total kilometers driven, FP is the fuel price, EP is the electricity price. It is important to note that fuel economy is measured in liters per 100 kilometers (l/100km), electric consumption in kilowatt-hours per 100 kilometers (kWh/100km), fuel price in baht per liter (baht/l), and electricity price in baht per kilowatt-hour (baht/kWh).

3.2.5. Maintenance cost

Vehicle maintenance costs are essential due to the need for regular inspections, repairs, replacements, and upkeep as specified by the manufacturer. These maintenance activities include tasks such as replacing lubricants, filters, tires, and, in the case of EVs, batteries. Adhering to these maintenance schedules ensures the vehicle's longevity beyond the manufacturer's initial expectations. Each powertrain technology incurs different maintenance requirements and costs. This study employs a maintenance cost model tailored for various vehicle types based on manufacturer guidelines and recommendations from owner manual and periodical maintenance table by Toyota Motor Thailand Company Limited [29], MG Sales (Thailand) Company Limited [30], Honda Automobile Thailand Company Limited [31] and Rêver Automotive Company Limited [32].

Understanding maintenance costs is crucial for a comprehensive TCO analysis. Regular maintenance not only ensures optimal vehicle performance but also helps prevent more significant and costly repairs in the future. Maintenance might involve more frequent oil changes and engine-related services for ICEVs, while HEVs and PHEVs might require both conventional and electric powertrain maintenance. BEVs, on the other hand, typically have lower maintenance costs due to fewer moving parts and less frequent need for fluid replacements.

3.2.6. Insurance cost

Vehicle insurance is a crucial factor for consumers, as it helps mitigate the financial burden associated with various damages resulting from unexpected accidents. In the context of Thailand, there are two primary types of motor insurance:

- *Compulsory Motor Insurance: According to the Protection for Motor Vehicle Accident Victims Act of 1992, all vehicles must carry compulsory insurance. This requirement applies to vehicles with no more than seven passengers powered by either internal combustion engines or electric motors. Based on Thai General Insurance Association, the annual fee for this insurance is 645.21 baht [33].*
- *Voluntary Motor Insurance: This type of insurance covers damages exceeding the liability limits of compulsory motor insurance. The premium for voluntary insurance depends on several factors, including the vehicle's value and the driver's behavior. The cost determined by the insurance company, as detailed in Table 2, is used to calculate the TCO [34].*

Table 2. Voluntary Motor Insurance cost for each vehicle.

Model	Powertrain	Sum Insured, baht	Premium, baht
Toyota Corolla Cross 1.8 Sport Plus	ICEV	50,000 – 1,000,000	13,500 – 16,500
Toyota Corolla Cross HEV Safety	HEV	50,000 – 1,000,000	13,500 – 16,500
MG HS Turbo X	ICEV	50,000 – 1,200,000	13,500 – 17,500
MG HS PHEV X	PHEV	50,000 – 1,400,000	13,500 – 18,500
MG ZS 1.5 X	ICEV	50,000 – 800,000	13,500 – 15,500
MG ZS EV X	BEV	450,000 – 740,000	31,000
Honda HR-V e: HEV EL	HEV	50,000 – 1,000,000	17,000 – 21,000
BYD Atto3 480km	BEV	630,000 – 1,000,000	31,000

Incorporating insurance costs into the TCO model is essential for a comprehensive financial assessment of vehicle ownership. Compulsory insurance ensures basic coverage for all vehicle owners, while voluntary insurance provides additional protection and covers a broader range of potential damages.

3.2.7. Annual tax cost

In Thailand, vehicle tax is calculated according to the Motor Vehicle Act of 1979. For ICEVs, HEVs, and PHEVs, the tax is determined based on engine displacement, measured in cubic centimeters (cc). Conversely, for BEVs, the tax is calculated based on the vehicle's weight. This approach reflects the differing characteristics and regulatory frameworks applicable to various powertrain technologies.

Engine displacement-based tax systems typically impose higher taxes on vehicles with larger engines, incentivizing the purchase of smaller, more fuel-efficient vehicles. In contrast, weight-based taxation for BEVs considers the vehicle's total mass, aligning with policies aimed at promoting lighter and more efficient electric vehicles. This method also accounts for the fact that BEVs do not have traditional engines, making displacement-based taxation inapplicable [35].

Incorporating these tax calculations into the TCO model ensures a comprehensive assessment of all financial obligations associated with vehicle ownership. Accurate tax calculations are crucial for providing a realistic comparison of different vehicle types, considering both direct costs, such as purchase price and fuel, and indirect costs, such as taxes and maintenance.

Additionally, vehicle tax policies can significantly influence consumer behavior and market trends. For instance, countries implementing tax incentives for low-emission vehicles have seen increased adoption rates of HEVs and BEVs [36]. By reflecting these tax policies in the TCO analysis, this study provides insights into the potential impact of tax structures on vehicle choice and the broader market dynamics.

3.2.8. Discount cost

The discount rate is employed to convert future income or expenses into their present value, reflecting the time value of money. This concept is critical in studies assessing lifetime costs, particularly over long-term periods. The discount rate demonstrates the impact of time on the value of money, enabling the calculation of present expenses at the time of vehicle purchase. The present value PV is calculated using the following equation:

$$PV = \frac{FV}{(1+r)^t} \tag{6}$$

where PV represents the present value, FV is the future value, r is the discount rate, and t is the year of ownership.

In this study, a discount rate of 5% is applied, based on the recommendations from the Thailand Greenhouse Gas Management Organization (TGO) for evaluating greenhouse gas mitigation measures [37]. This discount rate is chosen to accurately reflect the financial implications over the vehicle's lifespan, ensuring a precise assessment of the total cost of ownership (TCO). By incorporating the discount rate, this analysis provides a comprehensive understanding of the present costs associated with future financial obligations, facilitating more informed decision-making regarding vehicle purchases and long-term investments.

The choice of discount rate is crucial in TCO analysis as it directly affects the valuation of future costs and benefits. According to studies such as those by Hackbarth and Madlener [36], the discount rate can significantly influence the perceived economic attractiveness of energy-saving technologies, including EVs. Lower discount rates generally increase the present value of future savings, making investments in more efficient but typically higher upfront-cost technologies like EVs more appealing.

Furthermore, applying an appropriate discount rate is vital for policy evaluations and long-term planning. For instance, the Intergovernmental Panel on Climate Change (IPCC) often uses discount rates in its models to assess the cost-effectiveness of various mitigation strategies over extended periods. By adopting a 5% discount rate, this study aligns with both local recommendations and international practices, ensuring robust and relevant financial analysis.

4. RESULTS AND DISCUSSION

4.1. The 10-Year TCO Model

The TCO for selected SUV vehicles was analyzed by categorizing the comparison into four distinct groups and comparing the highest-selling models of BEV, HEV, and ICEV. The TCO comparisons provide cost estimates over a ten-year ownership period, assuming an average annual mileage of 20,000 km as a baseline scenario. These estimations are depicted in Fig. 2.

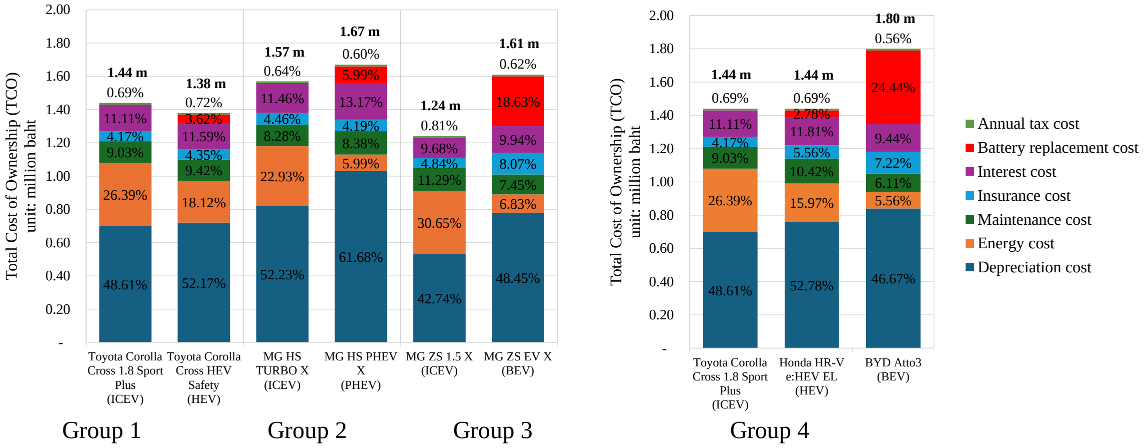


Figure 2. The TCO model over ten years of the sample vehicles (baseline scenario).

In Group 1, the comparison between the HEV and ICEV (Toyota Corolla Cross) reveals that the TCO of HEVs is 4.17% lower than that of ICEVs, with the HEV costing 1.38 million baht and the ICEV costing 1.44 million baht. Analyzing the TCO structure, it was noted that HEV incurs a significant battery replacement cost, accounting for 3.62% of the total TCO. In terms of depreciation, the HEV is 3.56% higher than the ICEV. Conversely, the energy cost of the HEV is 8.27% lower than that of the ICEV. The proportions of maintenance, insurance, interest, and annual tax costs are comparable between both vehicle types.

In Group 2, the comparison between the PHEV and ICEV (MG HS) reveals that the TCO of the PHEV is 6.37% higher than that of the ICEV, with values of 1.67 million baht of the PHEV and 1.57 million baht of the ICEV. Notably, the battery replacement cost of the PHEV accounts for 5.99% of the total TCO. Furthermore, the depreciation cost of the PHEV is 9.45% higher than that of the ICEV. Conversely, the energy cost associated with the PHEV is significantly lower, at 16.94% less than that of the ICEV. Costs related to maintenance, insurance, interest, and annual tax are comparable between the two vehicle types.

In Group 3, the comparison between the BEV and ICEV (MG ZS) demonstrates that the TCO of the BEVs, at 1.61 million baht, is 29.84% higher than that of the ICEV, which stands at 1.24 million baht. The TCO analysis of the BEV indicates substantial battery replacement cost, constituting 18.63% of the total TCO. Additionally, the depreciation cost of the BEV is 5.71% higher than that of the ICEV. However, the BEV shows significantly reduced energy and maintenance costs, which are 23.82% and 3.84% less than those of the ICEV, respectively. Costs related to insurance, interest, and annual tax remained roughly equivalent across both vehicle types.

For the final group, which includes the best-selling models among BEV, HEV, and ICEV, the analysis reveals the following: The TCO of the BEV is 1.80 million baht, 25.00% higher than that of the ICEVs, which is 1.44 million baht. A detailed structure of the TCO of the BEV indicates that battery replacement costs account for 24.44% of the total TCO. In comparison, the energy cost and maintenance cost of the BEV are 20.83% and 2.92% lower than those of the ICEV, respectively. Depreciation, insurance, interest, and annual tax costs are found to be comparable. Conversely, the TCO of the HEV is the same as that of the ICEV at 1.44 million baht. The TCO structure of the HEV shows battery replacement costs representing 2.78% of the total TCO. Meanwhile, the depreciation and maintenance costs of the HEV are 4.17% and 1.39% higher than those of the ICEV, respectively, and energy cost is significantly reduced by 10.42%. Costs related to insurance, interest, and taxes remained proportionally similar across both vehicle types.

This comparative analysis across four groups highlights the diverse cost structures associated with different vehicle powertrains over a 10-year ownership period. It underscores the significant advantage of the lower energy costs of electrified vehicles (BEV, PHEV, HEV), offset by other higher expenses such as battery replacement and depreciation. These findings provide essential insights for consumers considering the long-term economic impacts of purchasing EVs versus traditional ICEVs.

4.2. Sensitivity Analysis

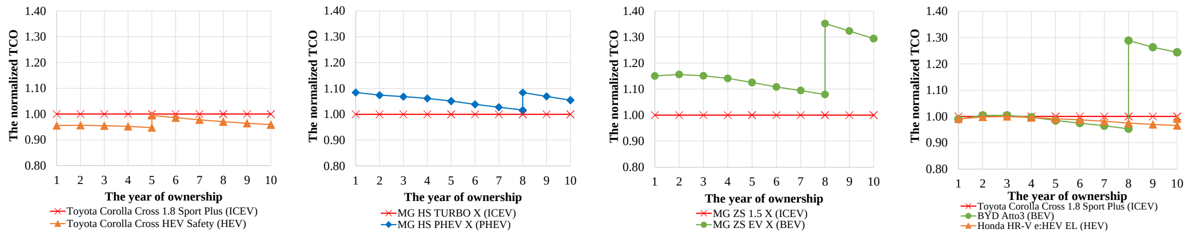
Fig. 3 presents the annual changes in TCO throughout the ownership period. This figure displays the comparative results for the considered groups, with the TCO of the ICEV in each group set as the baseline (normalized to a ratio of 1) for the entire tenure. This normalization facilitates a clear visual comparison of the TCO ratios across different vehicle powertrains.

In Fig. 3(a), the analysis of the TCO ratio for the HEV relative to the ICEV shows an initial 4.46% lower TCO for the HEV, which gradually decreases by 0.20% annually until the 5th year. A notable increase of 5.01% occurs in the 5th year, corresponding to battery replacement. Following this, the TCO ratio for the HEV continues to decrease, averaging a decline of 0.66% per year until the 10th year.

In Fig. 3(b), the TCO ratios for the PHEV relative to the ICEV begin with an 8.45% higher ratio, decreasing by 0.96% annually until the 8th year. A significant increase of 6.63% is observed in year 8, attributed to battery replacement. Following this increase, the TCO ratio continues to decline, averaging a decrease of 1.46% per year until the 10th year.

In Fig. 3(c), the BEV maintains a consistently higher TCO compared to the ICEV, mirroring the trend observed in the PHEV versus ICEV comparison. Starting 15.02% higher, the BEV's TCO ratio decreases by 1.13% annually until a substantial 25.24% increase in the 8th year from battery replacement, then resumes a downward trend of 2.91% annually until the 10th year.

In Fig. 3(d), the TCO ratios of the highest-selling BEV, HEV, and ICEV are compared. The BEV begins with a TCO ratio 1.04% lower than the ICEV, decreasing by 0.65% annually until a significant rise of 35.20% in the 8th year due to battery replacement, followed by a decrease of 1.95% annually. Conversely, the HEV starts 0.94% lower, decreasing steadily by 0.37% annually, with a slight increase of 2.69% in the 10th year due to battery replacement. These insights highlight the diverse financial impacts of adopting electrified vehicle technologies compared to traditional ICE vehicles, underscoring the long-term economic implications of electrified vehicle ownership.



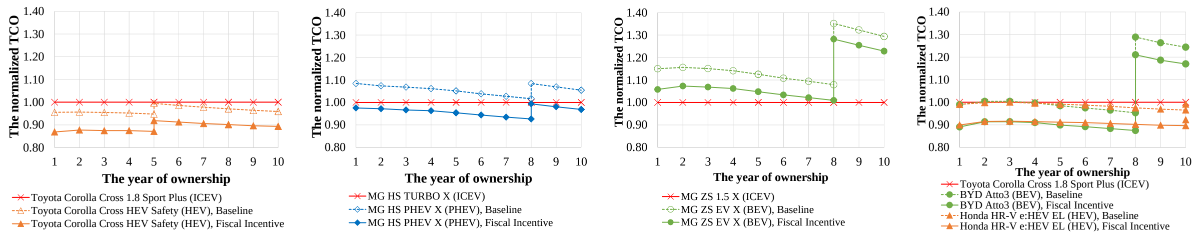
(a) (b) (c) (d)

Figure 3. Comparisons of normalized TCOs of the considered vehicles (Baseline scenario): (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4.

4.2.1. Scenario-1: Fiscal incentive

The first scenario is structured around fiscal incentives involving complete tax exemptions, which could be supported in initial purchasing by the government. This analysis compares the TCO ratios of EVs and ICEV under two conditions: the baseline scenario and one with fiscal incentive. Again, it is assumed that each vehicle travels an average of 20,000 kilometers annually throughout a ten-year ownership period.

The purchase price of all vehicles is typically composed of excise tax, local tax, and value-added tax (VAT). For the vehicles analyzed, local tax and VAT were fixed at 10% and 7%, respectively. However, excise tax varied substantially among vehicle types: 20% for ICEVs, 4% for HEVs and PHEVs, and 2% for BEVs. Under the fiscal incentive scenario, all taxes were eliminated. Fig. 4 presents the TCO ratios for the four vehicle groups following the tax reduction.



(a) (b) (c) (d)

Figure 4. Comparisons of normalized TCOs of the considered vehicles (Fiscal incentive): (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4.

For Group 1, the TCO ratio of the HEV compared to the ICEV, illustrated in Fig. 4(a), consistently remains lower throughout the ownership period under both the baseline and the fiscal incentive scenarios. Specifically, the analysis shows that under the baseline conditions, the HEV already has a competitive edge over the ICEV with a TCO reduction of 4.17%. This advantage is further amplified under fiscal incentives, where the TCO reduction reaches 10.66%. This significant decrease in TCO under fiscal incentives underscores the effectiveness of tax reductions in promoting the HEVs as a cost-effective alternative to the ICEVs. However, the data also indicate that the HEVs are economically viable without fiscal support, maintaining a lower TCO than the ICEVs, even in the absence of tax incentives. These findings highlight the inherent efficiency and potential market competitiveness of HEVs in comparison to traditional ICEVs. This suggests that while fiscal incentives can enhance the attractiveness of HEVs, they are not strictly necessary for HEVs to be a viable economic choice in the automotive market.

For Group 2, the TCO comparison between PHEV and ICEV illustrates a distinct impact of fiscal incentives on PHEVs' market competitiveness. As depicted in Fig. 4(b), the TCO ratio for the PHEV compared to the ICEV under fiscal incentives remains consistently lower throughout the ownership period. This contrasts sharply with the baseline scenario, where the PHEV consistently exhibits a higher TCO than the ICEV. With the application of fiscal incentives, the TCO for the PHEV is reduced by 3.11% relative to the ICEV, demonstrating that fiscal measures are crucial for PHEVs to be economically competitive with ICEVs. This reduction highlights the effectiveness of tax relief and subsidies in lowering the upfront and ongoing costs associated with owning a PHEV, thus enhancing its attractiveness to consumers. These fiscal policies play a pivotal role in aligning the TCO of PHEVs more closely with that of traditional ICEVs, fostering a more competitive market for electrified vehicles.

For Group 3, the TCO comparison between the BEV and ICEV reveals nuanced effects of fiscal incentives on the competitiveness of BEVs. As illustrated in Fig. 4(c), the TCO ratio for the BEV, when supported by fiscal incentives, remains higher than that for the ICEV until the 6th year of vehicle ownership. However, from the 6th year onward, the TCO for the BEV drops below that of the ICEV, although this advantage is temporarily reversed in the 8th year due to costs associated with battery replacement. Based on the baseline scenario, without any fiscal incentive, the TCO for the BEV consistently exceeds that of the ICEV throughout the vehicle ownership period. This indicates that while fiscal incentives do help reduce the TCO for BEVs, they alone are insufficient to make BEVs cost-competitive with ICEVs from the outset. The analysis suggests that additional supports, such as enhanced charging infrastructure, subsidies for battery technology, or reduced electricity rates for EV charging, are crucial for making BEVs a more viable economic choice in comparison to ICEVs. These combined measures would likely provide a more sustained and effective reduction in the TCO for BEVs, enhancing their market competitiveness throughout the ownership period.

For Group 3, Fig. 4(d) presents a comparison of the TCO ratios for the highest-selling BEV, HEV, and ICEV under baseline and fiscal incentive scenarios. It highlights that both the HEV and BEV can achieve a lower TCO than the ICEV under supportive fiscal conditions, with the BEV showing a more pronounced response to such incentives, especially in the initial years of ownership. The HEV maintains a consistent advantage over the ICEV, with even slight improvements under fiscal incentives. The BEV, while initially close to the ICEV under the baseline scenario, benefits significantly from fiscal incentives, dropping below the ICEV baseline from the first year and maintaining lower costs except during periods such as battery replacement. The findings underscore the effectiveness of fiscal incentives in making EVs more economically competitive against traditional ICEVs, highlighting the potential cost savings over time with the adoption of greener technologies. However, additional support should be considered for BEVs.

This targeted reduction in taxation is designed to foster the adoption of environmentally friendly vehicles by substantially decreasing their initial purchase costs and, consequently, their overall TCO. The comparative analysis between the baseline and fiscal incentive scenarios in this study evaluates the efficacy of fiscal policies in expediting the shift toward sustainable automotive technologies. This assessment highlights the critical role of supportive measures in promoting a cleaner, more sustainable transportation sector.

4.2.2. Scenario-2: Battery price discount

The second scenario examined in this study investigates the impact of a significant reduction in battery prices on the TCO when the battery is replaced during the ownership period. It compares the TCO ratios of the EVs against ICEV under two scenarios: the baseline scenario and a scenario where battery prices for EVs are discounted by 60%. Again, each vehicle is assumed to be driven an average of 20,000 kilometers per year over a ten-year ownership period. This scenario aims to assess how significant reductions in battery costs could influence the economic competitiveness of EVs, potentially accelerating their adoption by making them more financially accessible compared to traditional ICEVs. This comparison not only helps quantify the direct benefits of lower battery costs but also illustrates the potential shift in consumer preference towards more sustainable automotive options as economic barriers are minimized. The TCO ratios of the considered four groups of vehicles after reducing the battery price are illustrated in Fig. 5.

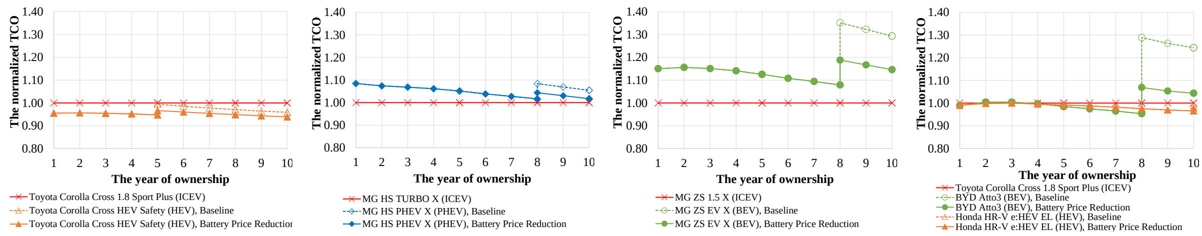
For Group 1, the TCO ratio of the HEV compared to the ICEV remains lower across both the baseline and the reduced battery cost scenarios throughout the vehicle ownership period. A detailed examination of the TCO ratios from the baseline HEV to the HEV with decreased battery costs reveals that such financial support has minimal impact on the overall TCO. This minimal effect is likely attributable to the relatively modest portion of battery costs in the total expenses of HEVs. Consequently, the reduction in battery prices does not significantly enhance HEV's economic competitiveness since it is already cost-effective compared to ICEV without any battery cost reductions, as demonstrated in Fig. 5(a). This analysis suggests that the HEV inherently poses a competitive edge over the ICEV in terms of ownership costs, reducing the necessity for specific incentives targeting battery price reductions.

For Group 2, the TCO ratio of the PHEV compared to the ICEV remains higher for both the baseline and the reduced battery cost scenarios throughout the vehicle ownership period. Analysis of the TCO ratios, as illustrated in Fig. 5(b), indicates that even with a substantial 60% reduction in battery costs, the decrease in TCO for the PHEV is only marginal, at about 1%. This slight reduction suggests that lowering battery prices does offer some financial relief, and it is insufficient for PHEVs to achieve cost parity with ICEVs. Consequently, this underscores the necessity for additional measures beyond battery cost reduction to enhance the economic attractiveness of PHEVs.

For Group 3, the TCO ratio of the BEV relative to the ICEV remains higher for both the baseline scenario and with a 60% reduction in battery costs throughout the ownership period. Detailed analysis, as illustrated in Fig. 5(c), reveals that even a significant reduction in battery prices results in only a modest 3% decrease in TCO for the BEV. This indicates that while lower battery costs provide some financial benefit, they are not sufficient on their own for BEVs to match the cost-effectiveness of ICEVs. Consequently, just like with PHEVs, additional interventions are necessary to make BEVs economically competitive. These may include enhanced fiscal incentives, subsidies, the development of charging infrastructure, or further technological advancements that reduce operational costs. This comprehensive approach is crucial to improving the market viability of BEVs.

For Group 4, Fig. 5(d) illustrates the TCO ratios for the highest-selling BEV, HEV, and ICEV. The TCO ratio for the BEV, before any adjustments to battery pricing, generally stays below the ICEV baseline, suggesting a lower TCO for most of the ownership period. However, an exception occurs in the 8th year, where the BEV's TCO ratio exceeds the baseline, likely due to substantial costs associated with battery replacement. When battery prices are reduced by 60%, the TCO for the BEV approaches but remains slightly above the baseline, indicating only a marginal reduction in overall costs. In contrast, the HEV consistently maintains a TCO ratio below the ICEV throughout the period, and the impact of the reduced battery price on its TCO is minimal, reinforcing the inherent cost-efficiency of HEVs over traditional ICEVs.

This scenario systematically evaluates the impact of a 60% reduction in battery costs on the TCO for EVs compared to ICEVs over a ten-year ownership period. The findings indicate that while reduced battery costs slightly decrease the TCO for BEVs and PHEVs, these reductions alone are insufficient to achieve cost parity with ICEVs. HEVs exhibit the least sensitivity to battery price reductions, maintaining a lower TCO relative to ICEVs throughout the period, underscoring their inherent cost efficiency. Overall, the study highlights the need for comprehensive strategies beyond just battery cost reductions, including fiscal incentives and infrastructure enhancements, to make EVs economically competitive and accelerate their market adoption. This approach will be essential in shifting consumer preferences towards more sustainable automotive options and overcoming the economic barriers currently hindering broader EV integration.



(a) (b) (c) (d)

Figure 5. Comparisons of normalized TCOs of the considered vehicles (Battery price discount): (a) Group 1, (b) Group 2, (c) Group 3, and (d) Group 4.

5. CONCLUSION

This study can be concluded as follows:

- *HEVs exhibit a lower TCO compared to ICEVs, with minimal impact from battery cost reductions. HEVs maintain cost efficiency due to lower energy costs and consistent cost advantages throughout the ownership period.*
- *PHEVs show a higher TCO compared to ICEVs, even with reduced battery costs. Significant fiscal incentives are essential to make PHEVs economically competitive.*

- *BEVs have a higher TCO compared to ICEVs, with battery replacement costs significantly impacting their economic viability. Substantial fiscal incentives and additional supportive measures are necessary for BEVs to achieve cost competitiveness.*
- *Fiscal incentives, such as complete tax exemptions, greatly enhance the BEV's economic competitiveness. Under these conditions, the BEV's TCO becomes more favorable, dropping below the ICEV's TCO in the initial years of ownership and remaining lower except during the battery replacement period.*
- *A 60% reduction in battery prices moderately impacts the TCO of the BEV, reducing it slightly but not enough to achieve cost parity with the ICEV.*
- *While the BEV has higher initial costs, it demonstrates potential long-term savings through lower energy and maintenance expenses, especially with supportive fiscal measures.*
- *The HEV presents a consistently cost-effective alternative to the ICEV, with balanced costs across various categories, making it an economically viable choice even without significant fiscal incentives.*

Based on the results reported in this study, it can be suggested that policies that support the reduction of TCO for EVs through financial incentives and infrastructure development should be implemented. These measures are critical to accelerating the adoption of EVs and achieving environmental and economic goals in Thailand.

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Appendix

Table A1. Vehicle specification for comparison vehicles from the ECO sticker by the Office of Industrial Economics, Thailand [22].

Model	Powertrain	Engine Size	Motor Size	Battery Capacity	Energy Consumption l/100km or Wh/km	Purchasing price (baht)
Toyota Corolla Cross 1.8 Sport Plus	ICEV	1.8L	-	-	6.5 or -	999,000
Toyota Corolla Cross HEV Safety	HEV	1.8L	53kW	19.50kWh	4.3 or -	1,024,000
MG HS Turbo X	ICEV	1.5L	-	16.60kWh	6.2 or -	1,159,000
MG HS PHEV X	PHEV	1.5L	90kW	1.69kWh	6.2 or 140	1,379,000
MG ZS 1.5 X	ICEV	1.5L	-	-	6.4 or -	759,000
MG ZS EV X	BEV	-	130kW	50.30kWh	- or 150	1,023,000
Honda HR-V e:HEV EL	HEV	1.5L	96kW	n/a	3.9 or -	1,079,000
BYD Atto3 480km	BEV	-	150kW	60.48kWh	- or 149	1,199,900