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Research article

CALCOM: An integrated techno-economic and life-cycle environmental framework for electric vehicle assessment in Sri Lanka

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ABSTRACT

Electric vehicle (EV) adoption is accelerating worldwide, creating a need for comprehensive frameworks that assess economic feasibility and environmental performance. This study presents a context-adaptive levelized cost of mileage (CALCOM) framework to evaluate the economic and environmental performance of battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and internal combustion engine vehicles (ICEVs) under Sri Lankan conditions. The framework integrates discounted life-cycle cost (LCC), net present value (NPV), and greenhouse gas (GHG) emissions into a unified assessment model. Real-world operational ad cost data were collected from owners representing Nissan Leaf (BEV), Toyota Aqua (HEV), and Toyota Vitz (ICEV). The analysis included purchase cost, energy consumption, maintenance, battery replacement, salvage value, and environmental costs over a 10-year ownership period. The BEV achieved the lowest levelized cost of mileage of 0.080 USD/km which further decreased to 0.050 USD/km under renewable charging. Life-cycle GHG emissions were 59% lower than those of ICEV. Sensitivity analysis identified electricity price, annual distance travelled, and charging efficiency as the primary determinants of BEV competitiveness. Threshold analysis indicated that BEVs remain economically attractive when domestic electricity tariffs are maintained below 0.32 USD/kWh. The findings demonstrate that BEVs offer the greatest economic and environmental benefits and offer evidence-based guidance for policies supporting electric mobility in developing countries.

1. Introduction

Transportation is one of the main sources of fossil fuel usage, greenhouse gas (GHG) emissions, and air pollution across the globe. Due to the fast-growing population and technological advancement, there has been an increase in the need for transportation fuels, thereby leading to heavy reliance on fossil fuel-powered internal combustion engine vehicles [1]. Reducing emissions and promoting sustainable energy use in the transportation sector are critical global challenges. Electric vehicles (EVs) are widely recognized as a viable alternative to internal combustion engine vehicles ICEVs) for reducing dependence on fossil fuels and mitigating GHG emissions [2]. Recent studies have also investigated renewable energy-supported charging and hydrogen refueling infrastructure as complementary approaches for sustainable transportation [3]. In addition, recent research has focused on integrated sustainable transportation pathways, including renewable energy integration, alternative fuels, and new energy management strategies to mitigate transportation sector emissions [4].

Among the available electrified vehicle technologies, battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs) have gained significant attention in recent years [5]. With advancements in the technologies associated with batteries, power electronics, and charging stations, the global shift towards these vehicle technologies has accelerated. Accordingly, the adoption of BEVs has been increasing very fast in most developed nations [6] whereas adoption remains comparatively low in many developing countries. Initial vehicle costs, lack of availability of charging stations, driving range anxiety, electricity price fluctuations, and traction battery costs are some of the major reasons that hinder the growth of adoption rates [7,8].

Abbreviations: BEV, Battery Electric Vehicle; CALCOM, Context-Adaptive Levelized Cost of Mileage; CH_4, Methane; CO_2, Carbon Dioxide; EV, Electric Vehicle; GHG, Greenhouse Gas; GWP, Global Warming Potential; HEV, Hybrid Electric Vehicle; ICEV, Internal Combustion Engine Vehicle; IPCC, Intergovernmental Panel on Climate Change; LCA, Life-Cycle Assessment; LCC, Life-Cycle Cost; LCOM, Levelized Cost of Mileage; N_2O, Nitrous Oxide; NPV, Net Present Value; TCO, Total Cost of Ownership; USD, United States Dollar

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Multiple studies have examined the techno-economic and environmental performance of EVs in various countries. Studies conducted in the UK and China [9], Portugal [10], Belgium [11], and India [12] show that EVs can reduce both life-cycle costs and greenhouse gas emissions relative to conventional vehicles if proper conditions for electricity production are met. Yet, most of these studies use manufacturer-rated efficiencies and optimal operating conditions instead of realistic values based on consumer behavior. Additionally, the environmental performance of EVs is highly dependent on the country's electricity production composition [13]. Countries whose electricity production relies heavily on fossil fuels will likely see fewer environmental gains from using EVs in comparison to those producing electricity via renewable energy sources [9,10]. A Portugal case study by Freire & Marques [9] claims EVs can only be considered environmentally competitive with ICE vehicles if grid emissions fall below 800 gCO2eq/kWh.

The significance of EV operation analysis, charging management, and energy system integration has been further reinforced by recent research. The increasing penetration of EVs introduces additional challenges related to charging demand, grid stability, and energy management. Research on the optimal scheduling and uncertainty-aware planning of EV charging stations has shown that coordinated charging strategies can enhance the performance of the power distribution network, as well as the adoption of EVs in large numbers [14]. The results indicate that energy management strategies should be considered when assessing the sustainability and feasibility of EV deployment.

Furthermore, the adoption of renewable energy for EV charging has been a major focus, as it can help lower indirect emissions from electricity generation. In recent years, lifecycle assessment (LCA) and multi-objective optimization methods have been used to design renewable energy supply systems for EV charging stations. These studies suggest that the environmental and economic efficiency of EV charging systems is highly sensitive to the type of renewable energy sources used, the interaction between the grid and the charging system, and the operational strategies adopted [15].

Research on the manufacturing and disposal processes of EV batteries has been extensively studied. The production process of lithium-ion batteries requires high energy use for material extraction and processing, which contributes considerably to life-cycle greenhouse gas emissions [16,17]. The application of LCA methodologies has also expanded beyond transportation into other energy-intensive sectors, demonstrating its broader relevance in sustainability assessment frameworks [18].

Moreover, battery recycling and disposal processes consume similar energy. Hence, the assessment of the viability of EVs should take into consideration not only operational emissions and fuel savings but also production and disposal impact on the environment [19]. According to [20] BEVs offer zero tailpipe emissions and can reduce global GHG emissions by 50–70% over their total life cycles. In fact, [21] concludes that BEVs can only achieve true "zero-emissivity" if they are powered by renewable energy sources, either on a micro-scale or by transitioning the overall energy mix away from fossil fuels.

Other more recent studies using LCA have also emphasized the importance of considering the full life-cycle impacts when comparing EVs to conventional vehicles. The results of the environmental assessments under various operating conditions, such as ambient temperature variations, show that the overall environmental performance of EVs is significantly affected by climate conditions and energy sources [22]. Thus, regional electricity generation profiles, vehicle operating conditions and battery-related impacts should be taken into account in practical assessments, in addition to tailpipe emissions.

In addition, the recent progress in sustainable transportation research has highlighted the importance of a more comprehensive LCA approach to evaluate new energy technologies. While LCA has been used in various industries, its use in transportation offers insights into the upstream and downstream environmental impacts of energy production, manufacturing, operation, and end-of-life processes. These methods can help to make more reliable decisions in the context of sustainable mobility transitions [23].

The analysis of techno-economics generally relies on total cost of ownership (TCO) models to assess the economic viability of EVs [20,24]. Various studies have used various parameters in their analyses, including the period of ownership, methods of charging, electricity rates, and battery replacement strategies [25]. These parameters have led to varied results concerning the viability of EVs. For instance, several studies have demonstrated that driving conditions outside standard driving tests influence economic performance in practical settings [26]. Besides, other research suggests that incorporating renewable energy systems like roof-mounted solar panels could increase the economic viability of EVs [12].

1.1. The research objective and contribution

Although numerous studies have evaluated the technoeconomic or environmental performance of EVs, most existing research focuses on individual aspects such as total cost of ownership, life-cycle greenhouse gas emissions, renewable charging systems, or charging infrastructure optimization. A comprehensive assessment framework that simultaneously integrates discounted LCC, NPV, environmental costs, life-cycle greenhouse gas emissions, sensitivity analysis, and threshold analysis using real-world operational data remains limited, particularly for developing-country contexts [27]. Table 1 summarizes the characteristics and limitations of representative previous studies.

To address this research gap, this study proposes the Context-Adaptive Levelized Cost of Mileage (CALCOM) framework, which integrates techno-economic and environmental assessment within a unified analytical framework.

The main scientific contributions of this study are summarized as follows:

- Development of the proposed CALCOM framework, which integrates LCOM, NPV, life-cycle greenhouse gas emissions, and environmental costs within a unified assessment methodology.
- Integration of real-world operational and cost data collected from vehicle owners, providing a practical assessment based on actual operating conditions rather than solely relying on manufacturer-rated specifications.
- Development of a unified framework combining
- techno-economic analysis, environmental assessment, sensitivity analysis, and threshold analysis to comprehensively evaluate EV performance.
- Identification of practical electricity price and grid carbon intensity thresholds to support evidence-based policy decisions for EV adoption.
- Demonstration of the applicability of the proposed framework for evaluating EV technologies under developing-country operating conditions, providing a methodology that can be adapted to different regional and vehicle contexts through appropriate parameter modifications.

Rest of the paper is organized as follows. Section 2 contains the Material and Methods employed in this research, which include the techno-economic model, the environmental assessment approach, and data sources. The Results and discussion follow in Section 3 and are presented through a comparison of the techno-economic and environmental results, including a sensitivity analysis.

2. Material and methods

2.1. Case study vehicles and dataset

The representative case study vehicles considered in this research are the Nissan Leaf battery electric vehicle (BEV), Toyota Aqua hybrid electric vehicle (HEV), and Toyota Vitz internal combustion engine

Table 1
Comparison of representative previous studies and the proposed CALCOM framework.

Study	Assessment scope	Key assumptions	Strengths	Limitations
Freire & Marques [9]	Life-cycleenergy, GHGandcost analysis	Portugalelectricity mix	Integrated economicand environmental assessment	Country-specific assumptions;no real-worldoperational data
Macharis et al. [10]	Total cost of ownership	Commercial logistics vehicles	Detailed ownership cost analysis	Environmental impacts not evaluated
Singh et al. [11]	Solar-poweredEV charging	PV-basedcharging station	Renewableenergy integration	Vehicle life-cycle impacts not considered
Çiçek & S¸afak [28]	Renewablesupported hydrogen refueling station	MILP-basedenergy management	Integrated renewableenergy management	Focused on hydrogen vehicles rather than BEVs
Shaghaghietal. [16]	EV charging station planning	Uncertainty-aware scheduling	Grid-awarecharging optimization	Did not evaluate vehicle economics or emissions
Pg Abas et al. [27]	Techno-economic andenvironmental review	Global literature review	Comprehensive review of EV tech-nologies	No unified assessment framework or countryspecific application
Albrechtowicz [29]	Environmental assessment of EVs	Electricity generation source comparison	Highlights importance ofelectricity generation mix	Economic analysis not included

Table 2
Vehicle specifications and economic parameters used in the analysis.

Parameter	BEV	HEV	ICEV
Purchase price (USD)	11,000	13,333	11,667
Service cost (USD/year)	100	333	333
Tire cost (USD/Year)	240	240	240
Distance travelled (km/year)	24,000	24,000	24,000
12 V battery replacement cost (USD)	–	117	117
Traction battery replacement cost (USD)	1333	1000	–
Vehicle repairs (USD/year)	33	33	33
Insurance cost (USD/year)	267	267	267
Electricity efficiency (km/kWh)	7	–	–
Fuel efficiency (km/L)	–	20	10
Salvage income (USD)	3835	7873	6889
Other miscellaneous cost (USD/year)	33	33	33
Interest rate (%)	10	10	10
Vehicle depreciation rate (%)	10	10	10

vehicle (ICEV). These vehicles were selected because of their high market penetration and widespread use in Sri Lanka. The Nissan Leaf is one of the most used BEVs in the country, while the Toyota Aqua and Toyota Vitz were selected as representative HEV and ICEV models, respectively. Furthermore, Toyota passenger vehicles have a significant presence in the local vehicle fleet [29]. The selected vehicles belong to the same passenger vehicle category, enabling a fair comparison of their economic and environmental performance.

Real-world operational data were collected through both online and printed questionnaire surveys distributed among vehicle owners across Sri Lanka. A total of 425 valid responses were obtained, providing information on annual travel distance, electricity and fuel consumption, servicing and maintenance costs, battery replacement, insurance, charging practices, and salvage value estimates. These real-world data were complemented with manufacturer specifications and published literature to obtain the technical and economic parameters required for the analysis.

Table 2 summarizes the key vehicle specifications and economic parameters adopted in the proposed CALCOM framework. The selected parameters include the technical characteristics, operating costs, maintenance requirements, energy efficiency, battery replacement costs, financial assumptions, and salvage values required to estimate the LCC, NPV, and environmental impacts of the selected vehicles over the 10-year ownership period. The combination of survey data, manufacturer specifications, and literature-based parameters ensures that the analysis reflects representative operating conditions in Sri Lanka.

2.2. CALCOM framework configuration for vehicle assessment

A CALCOM model is developed to analyze the technical and economic viability, as well as the life cycle GHG emissions, of the three vehicle technologies under practical operating conditions. The proposed CALCOM framework was developed to offer a holistic evaluation tool that can concurrently assess the economic efficiency and life cycle GHG emissions associated with BEVs, HEVs, and ICEVs. The model overview is shown in Fig. 1.

The CALCOM model combines both techno-economic and environmental assessment measures to facilitate a comparison of the selected vehicle types. Techno-economic evaluation relies on the use of the LCOM measure. LCOM is an adaptation of the levelized cost of electricity (LCOE) concept. LCOM normalizes the LCC incurred by each of the selected vehicles on a per-kilometer basis, making a comparison possible between BEV, HEV, and ICEV technologies. NPV is introduced to address the time value of money and evaluate the economic feasibility of the selected vehicle technologies. Eq. 1 presents the formula used to calculate the LCOM.

$$\text{LCOM} = \frac{\sum_{t=1}^{n} \frac{\text{Net cash flow in} \quad 10 \quad \text{years}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\text{Distance travel in} \quad 10 \quad \text{years}}{(1+r)^t}} \tag{1}$$

Net cash flow is calculated by the difference between cash inflow and cash outflow. Eq. 2 summarizes all parameters used to calculate the LCOM of the vehicles.

$$\text{LCOM} = \frac{\frac{C_0}{(1+r)^1} + \sum_{t=1}^{T} \frac{E_t + F_t + S_t + T_t + B + R_t + I_t + M_t + Rec_t + Env_t}{(1+r)^t} - \frac{S_T}{(1+r)^T}}{D \ x \ T} \tag{2}$$

Where C_0 is the purchase cost, E_t is the electricity cost, F_t is the fuel cost, S_t is the service cost, T_t is the tire cost, B_t is the 12 V battery cost, R_t is the repair cost, I_t is the insurance cost, M_t is the miscellaneous cost, Rec_t is the recycling cost, Env_t is the environmental cost, S_T is the salvage value, r is the interest rate, D is the annual distance travelled, and T is the vehicle lifetime in years. The CALCOM framework's environmental component uses a cradle-to grave LCA to evaluate vehicle greenhouse gas emissions. It includes emissions from manufacturing, battery production, energy consumption, and recycling. This enables a complete life-cycle comparison of vehicle technologies, considering economic and environmental performance. The framework evaluates three phases, which are production, operational and end-of-life.

Using the proposed CALCOM framework, the Nissan Leaf, Toyota Aqua, and Toyota Vitz are comparatively evaluated using real-world

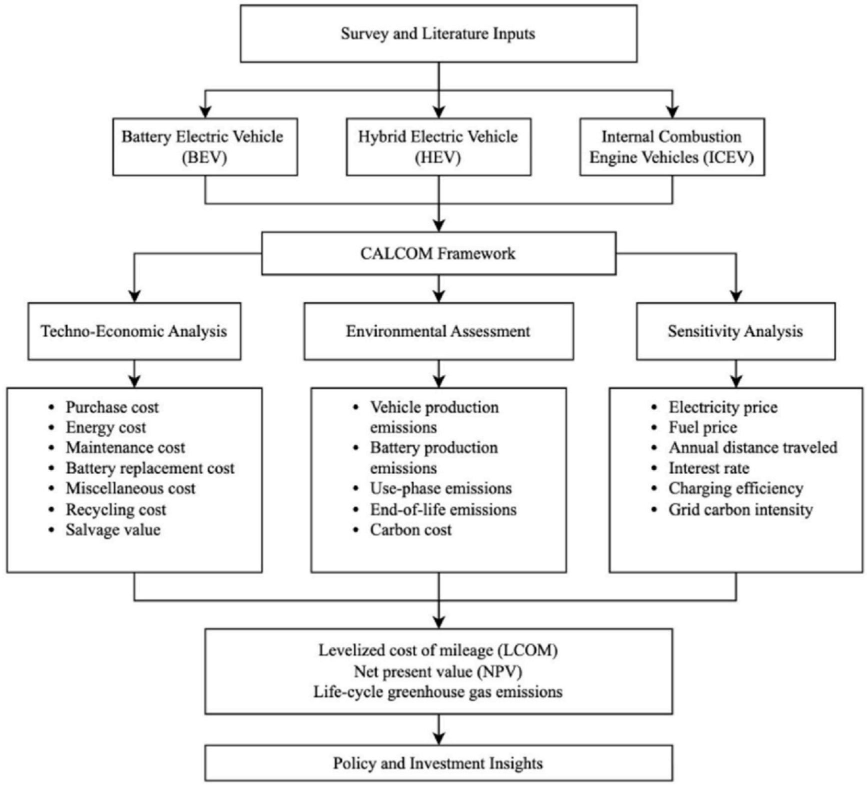

Fig. 1. Integrated CALCOM framework.

data received. The framework incorporates sensitivity analysis to investigate the impact of electricity tariffs, fuel prices, charging efficiency, annual distance travelled, interest rates, and grid carbon intensity on the techno-economic and environmental feasibility of the assessed technologies. This integrated workflow enables a realistic evaluation of electric vehicle adoption under developing-country operating conditions.

2.3. Vehicle energy consumption and operational efficiency estimation

The Nissan Leaf has a 24 kWh lithium-ion battery pack, the most common battery capacity identified in the survey. The Toyota Aqua HEV uses a hybrid battery system of 2 kWh whereas the Toyota Vitz runs fully on fuel. For the BEV, charging is assumed to occur at home using domestic electricity tariff rates. The electricity generation mix of Sri Lanka, which comprises coal, petroleum, hydro, biomass, and renewable energy resources, is taken into account for the environmental analysis [30].

The operational energy requirement of each vehicle is calculated based on the annual distance travelled, vehicle efficiency, fuel or electricity consumption, and battery charging efficiency. The corresponding operating cost is then determined using the prevailing electricity and fuel prices. The annual distance travelled by all vehicles is taken as 24,000 km. The average energy efficiency of the Nissan Leaf is 7 km/kWh, and that of the Toyota Aqua HEV and Toyota Vitz ICEV is 20 km/l and 10 km/l, respectively, as found from the data collected.

The annual electricity requirement of the Nissan Leaf is determined based on the energy consumed during battery charging. Charging efficiency losses are incorporated to account for energy losses occurring during the charging process estimated to be 85%. Energy demand is calculated by computing the energy required to travel annually according to the annual kilometers driven and the fuel efficiency of each car model. Petrol 92 is used as the fuel type for both HEV and ICEV vehicles and the current market price for petrol is $1.03 per liter. For BEV, the cost of electricity is $0.22 per kWh based on the maximum rate of domestic electricity charges during the study. It is assumed that the cost of electricity and fuel remains constant throughout the operational lifespan of the selected years.

This approach considers the realistic operational behavior, charging losses, and energy costs during operation to provide a practical evaluation of energy consumption patterns of each car model.

2.4. Techno-economic assessment methodology

This assessment evaluates the economic feasibility of the three vehicles in real-life conditions. Both initial and subsequent vehicle ownership costs are analyzed over the selected operational lifetime. The framework of LCOM considers the costs related to the capital and operation of the vehicle during its lifetime by taking into account the salvage revenue at the end of the selected period.

An operational lifetime of 10 years is assumed for all three vehicle types based on typical lifetimes and battery warranties found in the existing literature sources. The interest rate of 10% is used to represent current lending and economic conditions in developing countries.

Various cost parameters are taken into account in the techno-economic assessment framework. The cost of purchase refers to the initial capital investment required in the purchase of vehicles. The operational cost variables evaluated include electricity or fuel cost, service cost, maintenance cost, tire replacement cost, insurance cost, repair cost, and miscellaneous cost. The service cost includes routine services such as an oil change and filter change. The repair cost includes the costs incurred in case of mechanical failures or part replacements. Miscellaneous cost includes road taxes and parking costs, registration cost, among others.

The battery replacement is based on published battery degradation studies and manufacturer warranty information. The Nissan Leaf battery was assumed to be replaced in the eighth year, consistent with the typical eight-year traction battery warranty [31]. The Toyota Aqua hybrid battery was assumed to be replaced once during the 10-year ownership period, based on survey responses and reported service practices. [16,19]. The cost of replacement of 12 V auxiliary batteries is also included for all categories of vehicles, based on their replacement frequencies.

The economic assessment also incorporated recycling and end-of-life costs associated with vehicle disposal. Due to the unavailability of a local system to recycle EV battery systems, international data on battery recycling costs are utilized [32]. Additionally, environmental costs are estimated by including greenhouse gas emission costs per tonne.

Eqs (3) and (4) present the formulations used to estimate the salvage value and environmental cost, respectively [33,34].

$$SV = PP\ (1\text{-}d)^n \tag{3}$$

Where S_V is the salvage value of the vehicle at the end of the ownership period (USD), PP is the initial purchase price of the vehicle (USD), d is the annual depreciation rate expressed as a decimal, and n is the ownership period in years.

$$C_{carbon} = \frac{P_{CO_2} E_{annual}}{D} \tag{4}$$

Where C_{carbon} is the carbon cost per kilometer (USD/km), P_{CO2} the cost per kilogram of CO2 equivalent emissions (USD/kg CO2-eq), E_{annual} is the annual operational phase emissions (kg CO2-eq/year), and D the annual distance travelled (km/year).

The economic analysis of the vehicle technology selection problem is done using the LCOM and NPV approaches. The LCOM technique is employed to calculate the standardized LCOM, whereas the NPV method is applied to examine the viability of the chosen vehicle technologies over their entire service lives.

2.5. Life-cycle greenhouse gas emission assessment

The environmental impact assessment is carried out to study the life cycle GHG emissions for BEVs, HEVs, and ICEVs under local operating conditions. Furthermore, the environmental assessment supports the LCOM by incorporating the environmental cost associated with greenhouse gas emissions over the vehicle lifetime. The CALCOM framework combines both LCC and environmental analyses into a single integrated assessment model.

The method used for estimating the total amount of GHG emissions is based on a cradle-to-grave LCA that is at the stages of production, operation, and disposal of the vehicles. However, the infrastructure emissions are excluded from the estimation.

For the production phase evaluation, the study evaluated both emissions from the manufacturing process of the vehicles and emissions from the manufacturing process of the batteries. For the vehicle manufacturing emissions, an estimation is carried out using the curb weight of the vehicles [35–37]. The emissions from the manufacturing process are proportional to the curb weight of the vehicle [19].

For the battery manufacturing emissions, the assessment is done separately, considering the large impact the production process has on the environment, especially with respect to lithium-ion and hybrid batteries. The battery capacities of the Nissan Leaf and Toyota Aqua, together with battery production emission factors obtained from the literature, were incorporated into the analysis.

Emissions generated during the operational stage are estimated independently according to the differences in powertrain technologies and energy sources among the vehicles. For the Nissan Leaf, operational emissions are assessed by considering indirect emissions resulting from electricity generation during BEV recharging operations. Biomass, petroleum, coal, major hydro, and renewable generation sources constitute the electricity generation mixture of Sri Lanka. Coal-fired and petroleum-fired generation contribute the largest share of operational greenhouse gas emissions associated with BEVs.

For the Toyota Aqua and Toyota Vitz vehicles, operational emissions are estimated by considering the fuel combustion emissions from petrol during operation. Emission factors of the fuel combustion process are calculated according to the IPCC Tier 1 methodology. CO2, CH4, and N2O emissions produced during the combustion process are considered when conducting the environmental evaluation. To convert CH4 and N2O into CO2-equivalent emissions, GWP100 values of the respective gases are obtained from the IPCC Sixth Assessment Report [38]. This calculation helped estimate all greenhouse gas emissions in terms of CO2 emissions.

The analysis of end-of-life emissions involved the estimation of emissions that occur during vehicle recycling and battery recycling. The emission during the process of vehicle recycling is evaluated through recycling emission factors dependent on vehicle curb weight [19,39]. The emissions from battery recycling are independently evaluated through recycling emission factors found in the literature. Given the absence of local facilities for the recycling of batteries from electric vehicles, international emission factors are used in the analysis.

The total life-cycle greenhouse gas emissions associated with the production, operations, and end-of-life stage of each type of vehicle are determined by summing up the emissions from all three stages. To facilitate comparison among vehicle types, the total greenhouse gas emissions are converted to emissions per kilometer travelled (kg CO2eq/km).

3. Results and discussion

In this section, the results of the techno-economic and environmental analysis of the three vehicles are presented and discussed. This includes the comparative assessment of the LCOM, NPV, the impact of environmental costs and renewable charging scenarios, and sensitivity analysis of key economic parameters, life-cycle greenhouse gas emissions, and threshold-based policy recommendations for promoting electric vehicle adoption locally.

3.1. Techno-economic performance

The developed techno-economic model is used to evaluate the economic performance of the Nissan Leaf, Toyota Aqua, and Toyota Vitz over the selected 10-year operational lifetime. Fig. 2 shows the LCOM values for each vehicle technology with environmental costs. To evaluate the impact of GHG emissions on vehicle ownership costs, an environmental cost is added to the LCOM model by assigning a carbon price of 80 USD per tonne of CO2-equivalent emissions [19,40]. Over the 10-year ownership period, the LCOM values for BEV, HEV and ICEV are about 0.08 USD/km, 0.107 USD/km, and 0.149 USD/km, respectively. This highlights that BEV exhibits the lowest cost per kilometer compared to the other options. The purchase price accounts for approximately 60% of the total LCC, which is consistent with the findings of [41], where the initial vehicle cost represented about 70% of the total LCC in the Mexican context. Furthermore, the life-cycle cost of BEVs was found to be less than that of ICEVs by approximately USD 20,000, coinciding with [42]. The NPV analysis showed the same economic trend as the LCOM results. The Nissan Leaf recorded the lowest discounted lifetime cost, followed by the Toyota Aqua and Toyota Vitz. This confirms that the BEV remains the most economically attractive option when the time value of money is considered.

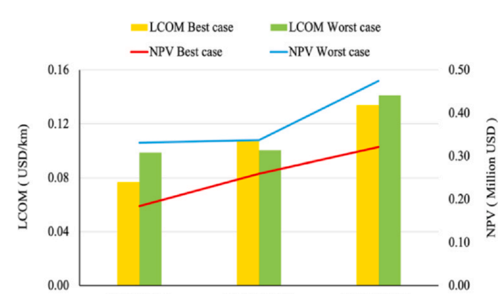

Fig. 2. LCOM and NPV including environmental costs.

The Nissan Leaf demonstrated a substantial cost advantage over the other two vehicle technologies. Compared to the Toyota Aqua, the BEV reduced the LCOM by approximately 38.5%, while compared to the Toyota Vitz, the reduction was approximately 51.6%. These results confirm that BEVs can provide significant long-term economic benefits under the prevailing electricity tariff and operating conditions analyzed.

More favorable economic performance of the BEV compared to other alternatives can be attributed to its lower operating and maintenance costs, which are consistent with previous techno-economic studies on electric vehicles [20]. Unlike ICEVs, BEVs do not require routine engine oil changes or exhaust system maintenance because of their simpler drivetrain configuration, resulting in lower maintenance costs [20]. Moreover, the high energy efficiency in terms of the amount of energy that the battery requires makes energy use cheaper as well. Even though battery replacement is taken into consideration, the low operating costs have been able to balance this.

The Toyota Aqua HEV demonstrates intermediate economic performance since it has an efficient hybrid engine with lower fuel consumption compared to a conventional petrol engine. However, despite having less fuel usage, the dependence of the Toyota Aqua on petroleum and hybrid battery replacement costs led to a higher LCOM as compared to the BEV. The Toyota Vitz had the highest LCOM because of its poor fuel efficiency. These results are consistent with previous studies. Studies have shown that EVs may be better options for total ownership costs than conventional vehicles under certain conditions, such as sufficient annual distance travelled [10–12]. The results from the analysis have supported these previous findings by using practical data under Sri Lankan conditions and have proven that BEVs could still be economically advantageous under these operating conditions.

The addition of environmental costs has led to an increase in LCOM for all vehicle types but has not impacted their relative positions. Further, any future increases in carbon prices will favor the lower-emitting vehicles, especially BEVs.

A renewable energy-based vehicle charging scenario is analyzed to assess the impact on the economic performance of the BEV. The data collected showed that most of the owners of Nissan Leafs have installed solar PV panels on rooftops and charged their vehicles through self-produced energy. The LCOM of the BEV decreased to 0.05 USD/km, representing a 28.5% reduction from the base case. These findings indicate that coupling BEVs with distributed renewable energy systems can further improve their economic performance, which is consistent with previous studies on renewable-powered EV charging [3,11].

3.2. Sensitivity analysis of the LCOM and NPV

3.2.1. Parameter sensitivity

To examine the effect of technical and economic factors on the LCOM of Nissan Leaf, Toyota Aqua, and Toyota Vitz, sensitivity analysis was performed taking into account electricity tariff, fuel price, annual distance travelled and interest rate. The analysis was performed to identify which parameters have the highest effect on long-term vehicle operation and to analyze the robustness of techno-economic conclusions based on them as shown in Fig. 3.

The electricity tariff has a significant effect on the economic characteristics as well as the NPV of the Nissan Leaf, as shown in Fig. 3(a). As the electricity price grew, so did the LCOM of the vehicle, which reduced the cost-effectiveness of this choice compared to hybrid and internal combustion engines. Nevertheless, according to the analysis, among all vehicle technologies, the BEV will remain the cheapest one.

Toyota Aqua and Toyota Vitz are highly sensitive to fuel prices since the growing fuel price increases their LCOM significantly, as shown in Fig. 3(b). The NPV results followed the same trend as the LCOM values. As electricity and fuel prices increased, the discounted lifetime costs of all vehicle technologies increased. However, the Nissan Leaf maintained the lowest NPV across the entire range of values analyzed.

The effect of annual distance travelled on the LCOM was evaluated, and the LCOM decreases as the annual distance travelled increases, as shown in Fig. 3(c). This is due to the dispersion of the initial cost, along with the annual expenses, over a higher distance travelled. Notably, the effect is more significant for the Nissan Leaf owing to its higher initial cost and lower operating cost, respectively. Similar behavior is observed in previous studies as well [43,44]. The trends therefore confirm that BEVs are particularly suitable for individuals with higher annual distance travelled. In contrast, the NPV shows an increment as the annual distance travelled increases, highlighting the low cost-effectiveness.

The interest rate is another factor influencing the LCOMs of vehicle types by affecting the discounted future expenses and salvage revenues. With higher interest rates, the LCOM became larger for vehicles

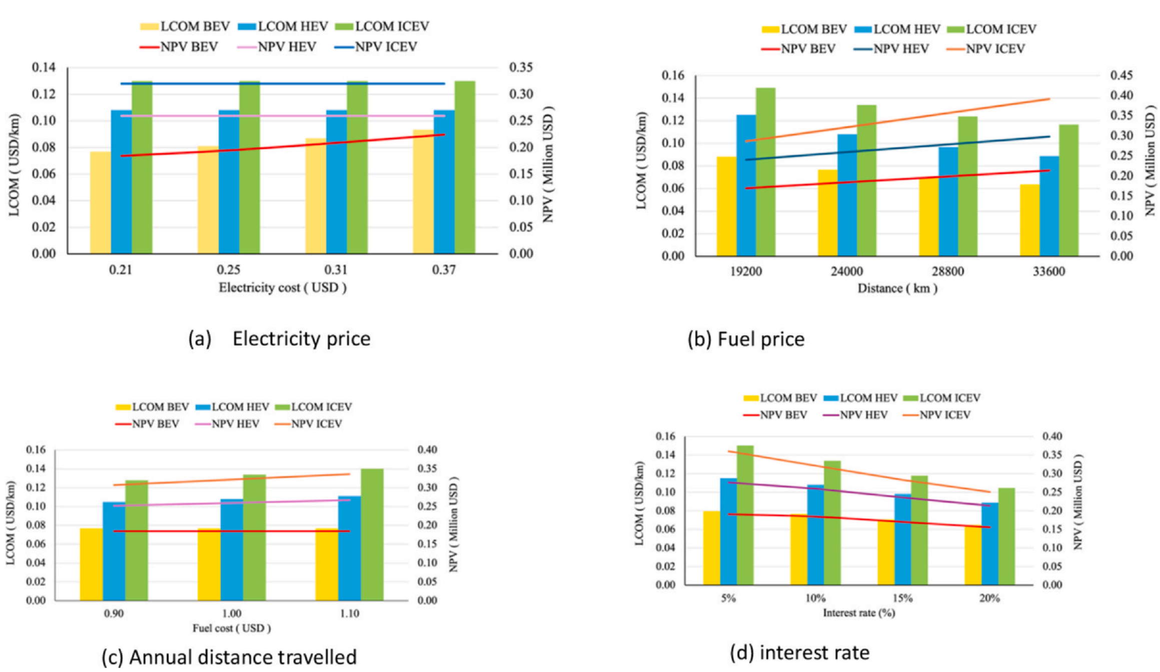

Fig. 3. Sensitivity of the LCOM and NPV to (a) electricity price, (b) fuel price, (c) annual distance travelled, and (d) interest rate.

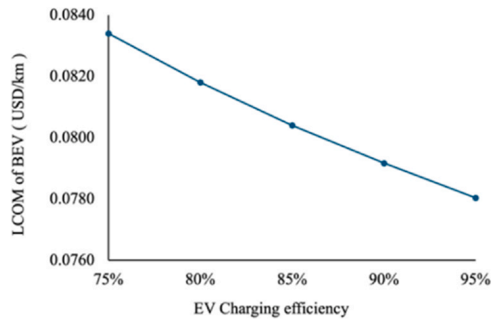

Fig. 4. Effect of charging infrastructure efficiency on LCOM.

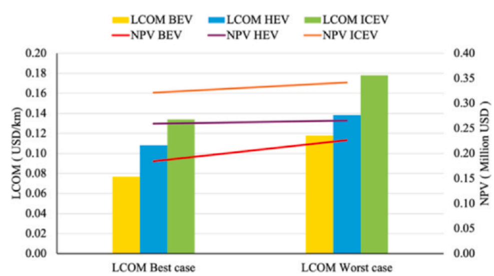

Fig. 5. Comparison of LCOM and NPV under base-case and worst-case scenarios.

Table 3
Base-case and worst-case parameters.

Parameter	Base Case	Worst Case
Interest rate	10%	20%
Annual distance travelled	24,000 km	19,200 km
Electricity price	0.22 USD/kWh	0.37 USD/kWh
Fuel price	1.03 USD/L	1.10 USD/L
Charging station efficiency	85%	75%

requiring an initial high capital investment, as shown by Fig. 3(d). As such, the Nissan Leaf had higher interest rate sensitivity compared to the Toyota Aqua and Vitz models due to its higher initial cost. Despite this, the BEV remained the least costly vehicle technology at all interest levels.

The effect of charging efficiency on the LCOM of the BEV is analyzed by varying the charging efficiency from 75% to 95%, as shown in Fig. 4. As the charging efficiency increases, the LCOM decreases almost linearly because a greater proportion of the purchased electricity is delivered to the vehicle battery, thereby reducing energy losses during charging. Consequently, less electricity is required from the grid to travel the same distance, resulting in lower operating costs. Although the reduction in LCOM is moderate, the results highlight that improvements in charging infrastructure efficiency can further enhance the economic competitiveness of BEVs, particularly over long-term vehicle operation.

3.2.2. *Scenario-based sensitivity analysis*

To complement the one-at-a-time parameter sensitivity analysis, a scenario-based sensitivity analysis was performed to evaluate the combined effects of favorable (base case) and unfavorable (worst-case) operating conditions on the LCOM and NPV of the selected vehicles. Fig. 5 compares the base-case and worst-case scenarios, and the individual parameters considered are in Table 3.

In both scenarios, the BEV has the lowest LCOM and discounted lifetime cost, followed by the HEV, with the ICEV being associated with the highest LCOM and discounted lifetime cost. These results confirm that the BEV remains the most economically attractive option under both favorable and unfavorable conditions, demonstrating the robustness of its long-term cost advantage.

The NPV results further confirmed the robustness of the findings. Under both base-case and worst-case scenarios, the Nissan Leaf exhibited the lowest discounted lifetime cost, demonstrating that the BEV remains economically competitive even under unfavorable market conditions.

While deterministic sensitivity analyses have been performed to identify the effect of important parameters on the economic viability of BEVs, future uncertainties remain. Electricity tariffs can vary because of the changes in energy markets, fuel price volatility, policy changes, and higher use of renewable energy sources. In addition, the cost of batteries is anticipated to decrease in the future because of the maturing technology, scale effects, and efficient recycling processes. This in turn might make BEVs more economically attractive than ever before. The increased number of charging stations and higher efficiencies of charging will also contribute to the reduction of operating expenses and increased convenience for users. Moreover, Sri Lanka's electricity generation profile is expected to evolve with greater integration of renewable energy sources. This transition will reduce the carbon intensity of electricity and consequently lower the life-cycle greenhouse gas emissions associated with BEVs. Hence, while the current results are informative in the selected scenarios, future research needs to consider the effect of uncertainties using stochastic methods such as Monte Carlo simulation.

3.3. *Life-cycle greenhouse gas emissions and carbon cost analysis*

The life-cycle greenhouse gas emissions of the compared vehicles are evaluated by considering production, operational, and end-of-life stages. The highest emissions during the vehicle production stage occurred for the Nissan Leaf since it is heavier and has a lithium-ion traction battery. Emissions from vehicle production for the Nissan Leaf were 5950.8 kg CO2, whereas emissions from battery production for the Nissan Leaf totalled 3384 kg CO2. Toyota Aqua generated fewer emissions from battery production owing to its smaller battery, and for Toyota Vitz it was negligible.

The highest emissions at the end of life occurred for the Nissan Leaf because of the greater size of the vehicle and the necessity of recycling the battery. Vehicle end-of life emissions are 3823.7 kg CO2 for the Nissan Leaf, 3223.0 kg CO2 for the Toyota Aqua, and 3076.5 kg CO2 for the Toyota Vitz. For Nissan Leaf, emissions from the battery end-of-life process were 1200 kg CO2, whereas the corresponding value for the Toyota Aqua is 75 kg CO2.

The operational phase emissions showed the opposite trend. The Toyota Vitz recorded the highest annual CO2 emissions at 5471.6 kg/year, followed by the Toyota Aqua at 2735.8 kg/year. The Nissan Leaf recorded the lowest annual operational CO2 emissions at 1159.0 kg/year since it does not produce direct tailpipe emissions, and its emissions are associated with electricity generation [45]. Methane (CH4) and nitrous oxide (N2O) emissions are also included by converting them into CO2-equivalent values using GWP factors. These emissions are smaller compared to CO2 emissions, but their inclusion improves the completeness of the LCA.

3.4. *Total life-cycle emissions*

The total cradle-to-grave emissions over the 10-year lifetime are 25,948 kg CO2 for the Nissan Leaf, 36,633 kg CO2 for the Toyota Aqua, and 62,581 kg CO2 for the Toyota Vitz, as shown in Fig. 6. Although the Nissan Leaf had higher production and end-of-life emissions, its much lower operational emissions resulted in the lowest total lifecycle emissions. The Toyota Vitz recorded the highest total emissions due to its continuous reliance on petrol during operation. The annual carbon

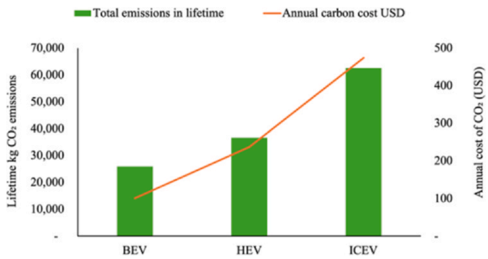

Fig. 6. Life-cycle greenhouse gas emissions and corresponding annual carbon costs.

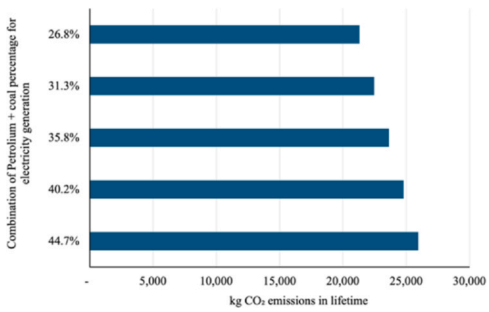

Fig. 7. Impact of fossil fuel share reduction on BEV life-cycle greenhouse gas emissions.

cost followed the same trend, with the highest value for the ICEV and the lowest value for the BEV as in Fig. 6.

3.5. Sensitivity analysis of greenhouse gas emissions

A sensitivity analysis is conducted to evaluate how different parameters affect the life-cycle emissions of BEVs. Along with the base case 24 kWh battery for the BEV, other available battery capacities of 40 kWh and 62 kWh are tested to assess the effect of larger battery packs on total life-cycle emissions. Increasing battery capacity increases total GHG emissions due to higher battery production and end-of-life emissions. The values recorded for 24 kWh, 40 kWh, and 62 kWh are 25,948.4 kg CO2, 29,004.4 kg, CO2 and 33,206.4 kg CO2, respectively, which is consistent with the findings reported by [46,47] and [48]. However, important to note that even with larger battery capacities, the BEV remained environmentally competitive compared to the HEV and ICEV options.

The impact of decarbonizing the electricity grid is assessed by reducing the proportion of coal and petroleum in Sri Lanka's electricity generation mix. The base case used Sri Lanka's actual electricity generation mix, in which coal and petroleum accounted for 44.7% of total electricity generation [49,50]. Four cleaner-grid scenarios are tested by reducing the fossil fuel share by 10%, 20%, 30%, and 40%. When the coal and petroleum share is reduced from 44.7% to 26.8%, the total life-cycle emissions of the Nissan Leaf decrease from 25,948 kg CO2 to 21,312 kg CO2, marking an 18% drop. These results demonstrate that the environmental benefits of BEVs increase as the grid becomes less carbon intensive as shown in Fig. 7.

3.6. Threshold analysis and policy implications

To provide practical guidance on the adoption of BEVs, a threshold analysis is carried out to identify the critical point at which BEVs remain more economical and environmentally preferable than their counterparts. Three variables are identified as key in determining whether BEVs are an economic choice compared to HEVs and ICEVs, namely: the fuel price, electricity price, and carbon content of the electricity grid and Table 4 summaries the results.

The sensitivity analysis identifies several policy measures that can significantly enhance the competitiveness of BEVs. Firstly, rising fuel prices due to market dynamics, policy shifts, or the elimination of fuel subsidies increase the economic appeal of BEVs since higher costs for running traditional vehicles are expected. Secondly, keeping domestic electricity tariffs not above 0.32 USD per kWh is crucial in ensuring the cost-effectiveness of BEVs compared to ICEVs and HEVs while also maintaining their competitive edge on an operating cost basis. Finally, the de-carbonization of the national power grid via the increased penetration of renewable energy sources can further enhance the environmental benefits of electric transport. According to the sensitivity analysis results, a reduction in the amount of fossil fuels used in electricity production by roughly 30% can decrease the BEV GHG emissions throughout the vehicle lifetime cycle by about 18%.

Although the study considered three representative passenger vehicle models, the proposed CALCOM framework is not limited to these vehicles. The framework is parameter-based and can be readily applied to other BEVs, HEVs, plug-in hybrid EVs, and ICEVs by updating the relevant technical, economic, and environmental input parameters. These include vehicle purchase price, battery capacity, energy efficiency, maintenance costs, battery replacement characteristics, electricity generation mix, and operational profiles. Furthermore, the framework can accommodate different battery technologies, such as lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries, by incorporating their respective manufacturing, degradation, and recycling characteristics. Consequently, the proposed CALCOM provides a flexible assessment methodology that can be adapted to different vehicle categories, operating conditions, and geographical regions.

4. Conclusion

This study developed a context-adaptive levelized cost of mileage (CALCOM) framework to evaluate the economic and environmental performance of battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and internal combustion engine vehicles (ICEVs) under Sri

Table 4
Thresholds for economic and environmental competitiveness of BEVs.

Parameter	Threshold	BEVadvantagevs. HEV	BEVadvantagevs. ICEV
Fuel price	≥ 1.03 USD/L (base); higher advantage above 1.16 USD/L	BEV cheaper by 40%	BEV cheaper by 55%
Electricity price Grid carbon intensity	Break-even0.32–0.34 USD/kWh;at0.22 USD/kWh, BEV is 65% cheaper/km ≤ Fossil share35% (320 g CO_2/kWh)	Retains advantage up to 0.32 USD/kWh Cleaner ≤ when fossil share 35%	Still lower up to 0.37 USD/kWh Cleaner ≤ when fossil share 45% (380 g CO_2/kWh)

Lankan operating conditions. The framework integrates discounted life-cycle cost, net present value (NPV) and greenhouse gas emissions, including environmental costs based on a carbon price, into a single assessment model. Real-world operational and cost data collected from 425 vehicle owners were used to compare the Nissan Leaf, Toyota Aqua, and Toyota Vitz over a 10-year ownership period.

The results demonstrate that the BEV achieved the lowest levelized cost of mileage at 0.080 USD/km, followed by the HEV at 0.107 USD/km and the ICEV at 0.149 USD/km. The BEV also exhibited the lowest life-cycle emissions, producing 25,948 kg CO2-eq compared to 36,633 kg CO2eq for the HEV and 62,581 kg CO2-eq for the ICEV. Sensitivity analysis identified electricity price, annual distance travelled, and charging efficiency as the most influential parameters affecting BEV competitiveness. Threshold analysis indicated that BEVs remain economically favorable when domestic electricity tariffs are maintained below 0.32 USD/kWh.

The findings confirm that BEVs provide the most cost effective and environmentally sustainable transport option among the technologies evaluated. The proposed CALCOM framework offers a practical tool for policymakers, researchers, and investors to assess vehicle technologies under local conditions and supports the formulation of evidence based policies for accelerating electric mobility in Sri Lanka and other developing countries.

CRediT authorship contribution statement

Anura Wijayapala: Supervision. **Nuwanthi Abeygunawardena:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Thanushika Jathunga:** Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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