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ELECTRIC VEHICLE'S LIFE CYCLE ASSESSMENT (LCA): LIFE CYCLE EMISSION (LCE) AND LIFE CYCLE COST (LCC) OF VARIOUS ELECTRIC VEHICLES

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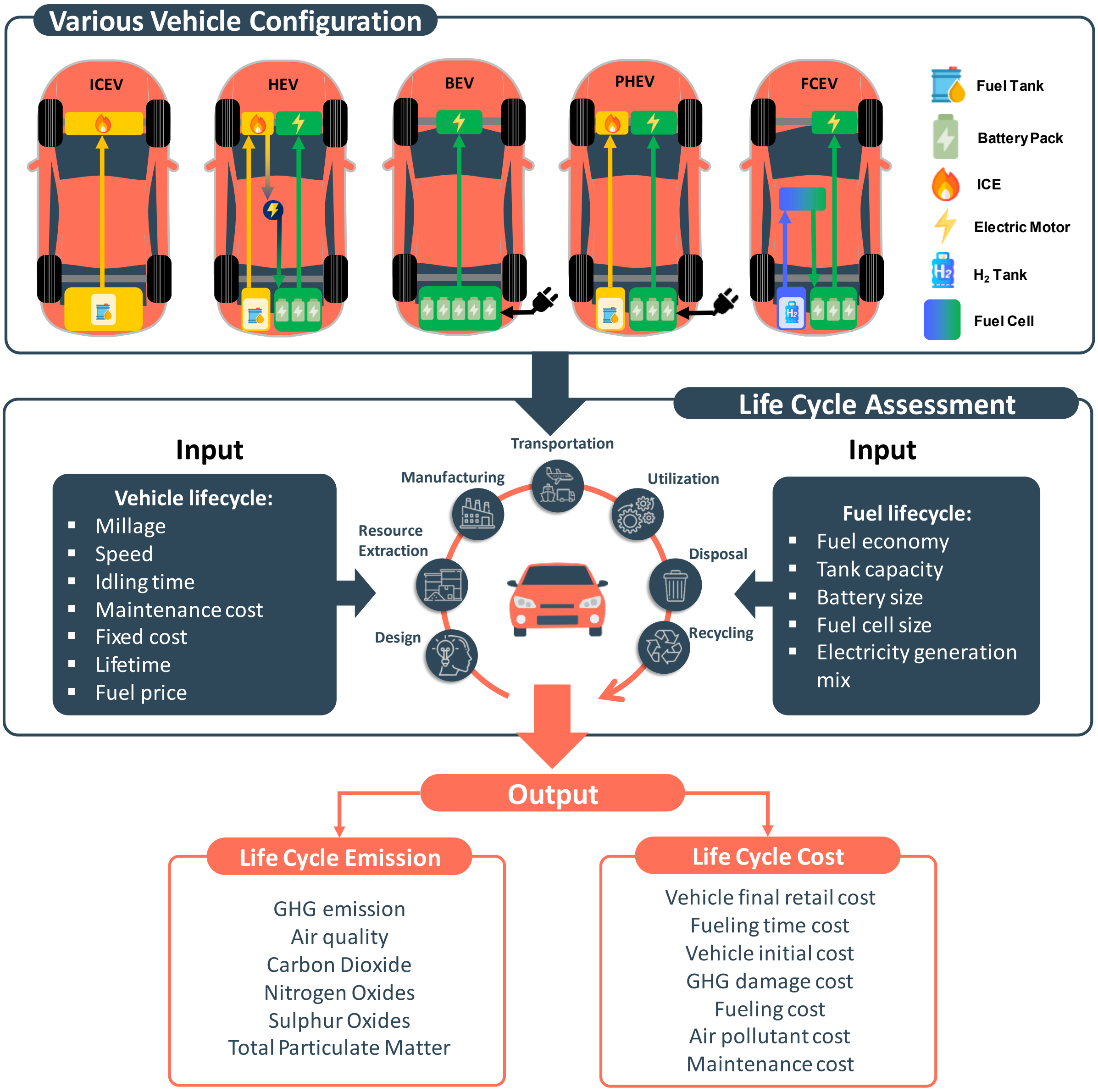
HIGHLIGHTS

- The study uses life cycle assessment to assess the environmental impacts of various electric vehicle types.
- Evaluating greenhouse gas emissions, the study compares the life cycle emissions and the cost of different electric vehicles in Malaysia.
- The study introduces a detailed life cycle cost framework, analyzing societal and consumer costs for electric vehicles.
- Comparative analysis favors hybrid electric vehicles as a cost-effective and low-emission alternative to internal combustion engines.
- The study suggests optimizing power grids, integrating renewable energy, and refining life cycle analysis to better understand electric vehicle impacts.

GRAPHICAL ABSTRACT



ABSTRACT

The rapid global shift toward sustainable transportation has driven many countries to explore cleaner technologies. As concerns regarding climate change intensify, researchers are increasingly focusing on technologies that can significantly reduce greenhouse gas (GHG) emissions. The transportation sector is a significant contributor to GHG emissions. High GHG emissions from transportation can be reduced using low-carbon fuels and electric vehicles (EVs). Among the various mitigation strategies, the advancement of EV technology has received considerable attention. EVs use an electric motor instead of an internal combustion engine to power vehicles. Life cycle assessment (LCA) measures a product's environmental effects from production to disposal. Several types of EVs were developed and introduced to lower GHG emissions. An evaluation of the environmental and economic value of each EV is thus required. This study investigates the LCA of several EVs. A case study in Malaysia is selected. The type of EVs includes hybrid electric vehicle (HEV), battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), and fuel-cell electric vehicle (FCEV). The life cycle emission (LCE) and life cycle cost (LCC) are compared for each EV and internal combustion engine vehicle (ICEV). The developed LCC framework comprises societal life cycle cost (SLCC) and consumer life cycle cost (CLCC). SLCC includes social impact, including EV first cost, lifetime operation, and external cost (emission cost). CLCC includes EV retail cost, lifetime operation cost, time loss and disposal cost. The simulation uses GREET Software to obtain GHG emissions and air pollutant intensities. The total LCC is calculated over an EV lifetime of 12 years. The study found that ICEV have the highest LCE, producing 417.52 g/mile, while FCEVs have the lowest emissions at 254.4 g/mile. However, the FCEV has the highest LCC with 1.08 $/mile. HEV is found to be the most viable option to reduce emission production with a LCC of 0.59 $/mile. The findings highlight that selecting the most sustainable vehicle technology requires balancing environmental performance with economic feasibility. While certain EV types deliver substantial emission reductions, their costs may still pose barriers to widespread adoption. The results provide valuable insight for policymakers, industry stakeholders, and consumers toward cleaner transportation strategies in the future.

Keywords: Life cycle electric vehicles; Life cycle assessment; Life cycle emission; Life cycle cost; Electric vehicle; Electric vehicle vs internal combustion engine vehicle

1. Introduction: Greenhouse Gas Emissions and Electric Vehicle (EV)

The transportation sector contributes significantly to greenhouse gas (GHG) emissions worldwide [1]. The transportation industry accounts for 28% of global GHG emissions, the highest share among other sectors. In general, GHG emissions consist of up to more than 80% of carbon dioxide (CO_2), along with a substantial amount of methane (CH_4) and nitrous oxide (N_2O) emissions [2]. The accumulation of GHG in the atmosphere traps heat, which raises global temperatures, causing climate change and human health problems [3].

Vehicular emissions have a significant impact on the sustainability of transportation as they can cause air pollution that damages the environment and human health [4]. Sustainable transportation aims to reduce these negative impacts by encouraging using environmentally friendly vehicles, such as EVs and energy-efficient public transportation. Adopting technologies and policies that reduce vehicle emissions, such as the use of alternative fuels and the development of infrastructure that supports sustainable transportation, is critical in creating a greener and more sustainable transportation system for the future [5].

Figure provides an overview of the sustainable transport system from production to the operation of vehicles. The relationships between resources represent the typical circular economy cycle, the market for vehicle production, the manufacturing of vehicles, material recycling, and reinsertion into a new production cycle. However, an energy and raw material-based operating cycle and society's means of adjusting transportation networks must be prioritized. Given that a significant portion of energy consumption in the transportation industry comes from road transportation, it becomes crucial to assess and address various strategies to mitigate emissions in the transportation sector.

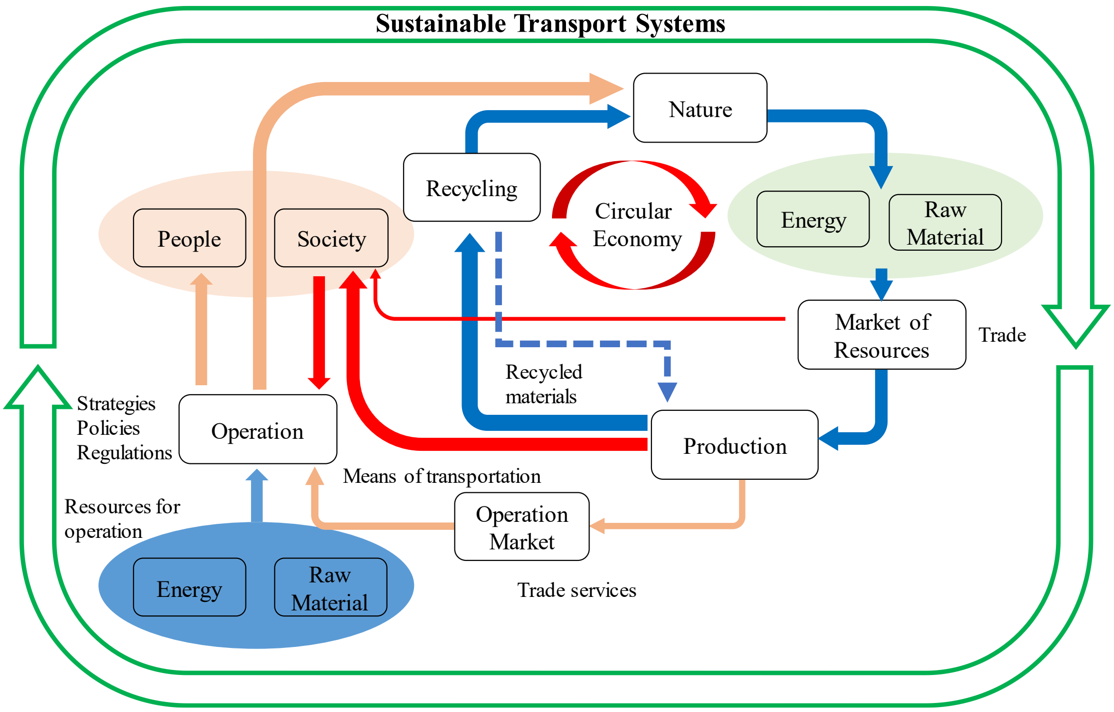


Figure 1. Overview of the development of sustainable transport systems (Reproduced from Machedon-Pisu and Borza [6]).

Strategies to reduce GHG emissions are specified into three broad categories: improvement in engine efficiency, introduction of low-carbon fuels, and reduction of vehicular miles traveled [7]. When considering alternatives to fossil fuels, Researchers must consider energy use, carbon dioxide emissions, and environmental impact.

The electrification of vehicles has gained interest among researchers due to its potential to emit lower emissions compared to internal combustion engine vehicle (ICEV) [8]. In addition, EVs perform better than ICE vehicles due to their efficient power trains and motors. EVs in the market have different power systems, driving ranges, and performance, making EV selection challenging. A structured method is therefore needed to compare each EV type.

Increasing GHG emissions levels throughout the years have been worrying due to their massive impact on the environment. Climate changes, global warming, extreme weather, and increased wildfires result from climate changes caused by GHG emissions. Several EV types have been invented and introduced due to the progress of EV technologies. Therefore, a better understanding of the environmental and economic relationship between each EV is required. Researchers have used the life cycle assessment (LCA) method to evaluate the environmental impact of EVs. However, a recent study on the life cycle cost and emission between EVs in Malaysia has not been discussed, with a lack of comprehensive and up-to-date comparisons of lifecycle emissions and cost among a wide range of EV models, including the latest emerging technologies. By addressing this gap, this study aims to provide a thorough understanding of different EV types' environmental impact and financial feasibility, thus guiding policymakers, manufacturers, and consumers toward sustainable transportation choices that align with the evolving EV market. The purpose of this study is to analyze the life cycle of emission and cost assessment of hybrid electric vehicle (HEV), battery electric vehicle (BEV), fuel-cell electric vehicle (FCEV), plug-in hybrid electric vehicle (PHEV) with ICEV as a benchmark.

2. Literature Review: Electric Vehicles and Life Cycle Assessments

The first EV was developed in the early 18th century. Since then, the evolution of EVs continued to arise until the technology of EVs stopped due to limitations in batteries and the rapid growth of ICEVs by the 1930s. The development of EVs continued in the 21st century due to interest in zero-emission electric vehicles (ZEV) [9]. Subsequently, several EVs have become available, including HEV, BEV, PHEV, and FCEV. Figure 2 shows the various EV configurations.

Raj and Appadurai [10] discussed the overview of HEVs. It comprises two separate systems: an internal combustion engine and an electric motor. The internal combustion engine system is powered by gasoline, while the electric motor uses electricity as a source of power. The electric motor connects to a rechargeable battery pack for electric mode driving. The flexibility between these two engines provides a solution for the ICEV. Its two-driving mode varies depending on the user's operating preference. One of the challenges of adopting a HEV is its expensive purchase cost due to the complexity of HEV systems.

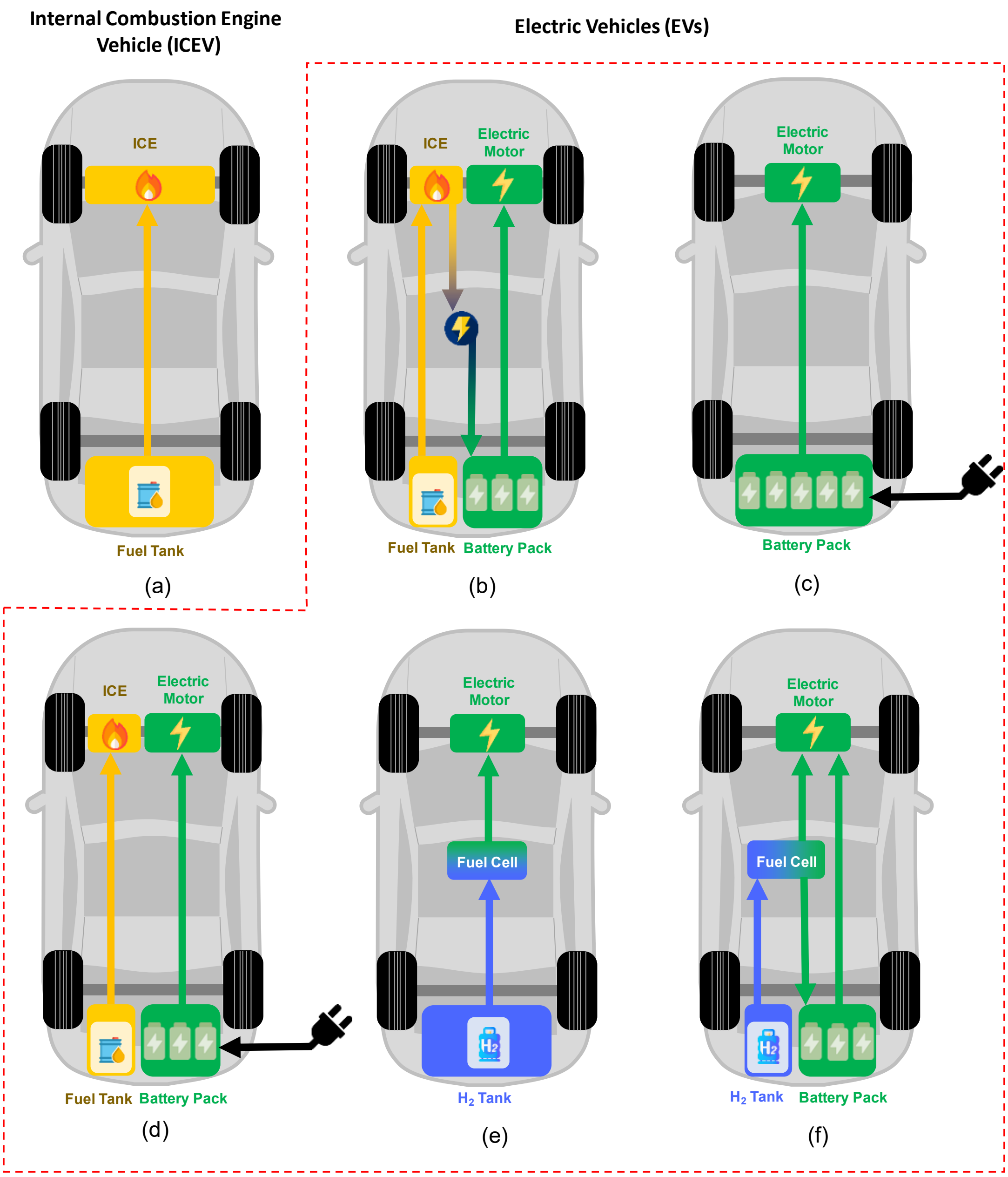


Figure 2. Vehicle configuration (a) ICEV, (b) HEV, (c) BEV, (d) PHEV, (e) & (f) FCEV.

On the other hand, BEVs are operated by electricity and have no internal combustion engine. Therefore, the reliance on fossil fuels as an energy source is eliminated. This provides excellent significance in adopting BEVs in the future. BEVs are also suitable for low-speed states and stop-go driving patterns, which are common in city driving due to the benefits of a regenerative braking system. In addition, EVs are suitable for operating at much lower loads compared to conventional internal combustion engine systems, which are more fit at relatively higher loads. Implementing a PHEV system bridges the gap between these two technologies.

Hybrid electric vehicles operate using petroleum fuel as their power source for the engine. In contrast, PHEVs are occupied with rechargeable battery packs and are available on the road and other charging outlets. The battery packs are set to be its source of power for shorter distances; once the battery has depleted to a certain state-of-charge (SOC), the vehicle will enter a hybrid mode for longer distances [11].

Fuel cell electric vehicles are powered by the chemical reaction of hydrogen and oxygen, which produces electric energy in the fuel cell, which consists of anode and cathode. The current produced inside the fuel cell is direct current (DC), while inverter is needed to produce alternating current (AC) [12]. FCEVs are superior to BEVs because they are lighter and smaller. FCEVs are also suitable for medium, large, and long-range vehicles. Ahmadi's research [7] found that among all the vehicle alternatives, FCEVs show significant results in emitting zero emissions during the operation phase.

Li et al. [12] studied the influencing factors that affect customer intention in adopting BEVs. Based on the results, the main situational barriers influencing customer intention are charging problems, purchase cost, and driving mileage range. Customers' inexperience regarding EVs, such as knowing the right time for service and maintenance, and awareness of customers were also discussed. For more accurate results, a large-scale dynamic survey with the studies of the three main influencing factors, which are demographic, situational, and psychological aspects, through experienced respondents, is required.

Muratori et al. [13] emphasize the current and future status, breakthroughs, and challenges in EV technology. The improvement of EV global adoption is the market potential for EVs to replace conventional light-duty vehicles (LDV) such as buses and diesel trucks. In terms of the performance evolution of batteries, power electronics, and electric machines, the price of lithium-ion battery packs has dropped significantly by 80% in the last 10 years. In addition, there is approximately one charging facility per 10-BEV in the US. It was found that grid decarbonization reduced GHG emissions of electric cars by at least 70%. Thus, the increase in the number of EV users is expected to continue with the price reduction and charging facilities. Based on the discussion above, each type of EV poses different driving ranges, charging times, electrical systems, maintenance costs, and life cycle emissions. Therefore, the selection between each of them is complex for research. The adoption of EVs, on the other hand, is limited by several factors, including charging time, total cost, and charging facilities. Consumers' failures to manage and adapt to EV technology and the inability to predict power consumption for a certain distance traveled are the major challenges in adopting EVs.

Kosai et al. [14] have done a comparative LCA on attributional and process basis to estimate the GHG emissions of petrol, biodiesel, and battery-powered vehicle. This study found that land-use change has no significant impact on biodiesel powertrains. Athanasopoulou et al. [15] evaluated the environmental behavior of BEVs compared to ICEVs for the European region through performing a well-to-wheel (WTW) analysis, as shown in Figure 3.

A study by Qiao et al. [16] examines the LCC and GHG emissions benefits in China. The evaluation was based on driving patterns and parameters such as velocity and acceleration. Charging infrastructure and battery pilots were also involved in the evaluation. It is found that recycling could only reduce GHG emissions but not in terms of cost. However, battery pilots can reduce the LCC.

In addition, Ayodele and Mustapa [17] reviewed and examined various published articles on life cycle analysis from 2001 to 2019. The variation of LCC depends on different policies and legislations in different countries. However, countries such as

Australia, Germany, and South Korea were fairly represented. The EV was found not cost-competitive with ICEVs due to the significant battery cost.

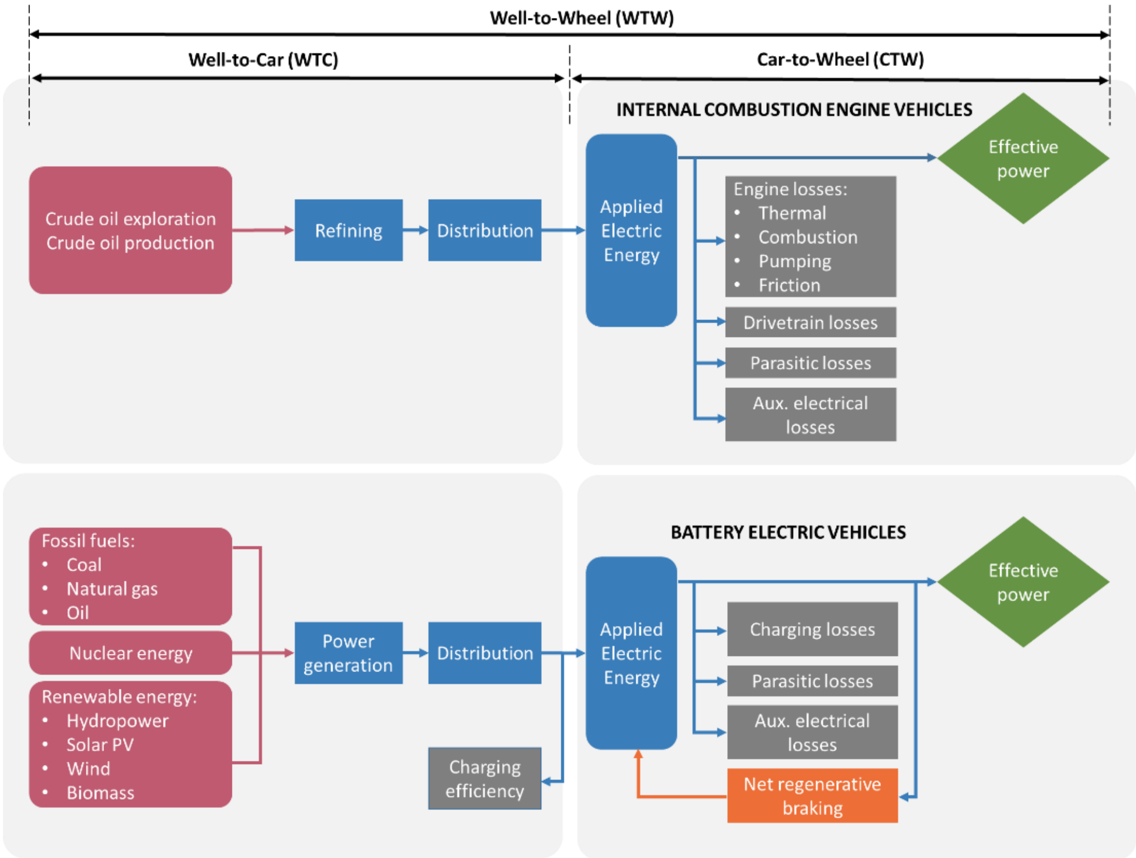


Figure 3. Entire energy flow framework for ICEV and BEV as basis of lifecycle emission (Reproduced from Athanasopoulou et al. [15]).

Verma et al. [18] compare the LCA and LCC analysis of EVs and ICEVs with fossil fuel as a fuel source. This paper review examines the adoption of EVs and its impact on various factors. It reveals that transitioning to EVs results in a positive outcome by reducing GHG emissions, benefiting the environment. However, it also highlights a concerning drawback – increased human toxicity levels due to the extensive use of metals, chemicals, and energy during powertrain and high voltage battery production. Additionally, the cost aspect is discussed, indicating that while EVs offer flexible pricing owing to uncertain future gasoline and electricity costs, the initial purchase cost remains higher due to expensive battery technology.

Qiao et al. [19] analyzes the GHG emissions of EVs in China throughout their life cycle. The study identifies that EV recycling can reduce half of the emissions of ICEVs, and the optimization of a cleaner power grid that utilizes renewable energy can further reduce the GHG emissions of the well-to-wheel (WTW) phase. Together, these studies indicate the LCC of vehicles varies depending on the vehicle model, type of EV, policies, and economic factors. The approach of LCC, which considers vehicle cost from the manufacturing of the vehicle to the disposal phase, is referred to as the cradle-to-grave (CTG) cycle. Another type is the cradle-to-cradle (CTC) cycle which involves processes from raw materials extraction, disposal, recycling, and reuse of the material. Each component of an EV has its own significance that impacts the overall LCC. It is important to note the significance of battery cost, powertrains, and battery pilot when LCC is being conducted. Table 1 shows key studies related to the emission of EVs and ICEVs.

Table 1. Relevant studies on EVs and ICEVs emission

Article	Findings	Reference
Electric vehicle and driving towards sustainability: Comparison between EV, HEV, PHEV, and ICE vehicles to achieve net zero emissions by 2050 from EV	HEV is a choice for sustainability due to its balance in cost, emissions and maintenance.	Veza et al. [20]
Life cycle assessment of EVs and ICEVs: A case study of Hong Kong	Based on the Hong Kong power generation mix, EV has the lowest environmental impact in the future scenario.	Shafique et al. [21]
Factors influencing global transportation electrification: Comparative analysis of electric and ICEVs	EV adoption was found to be impacted by factors including vehicle performance, charging infrastructure, government policy, and social influences.	Tan et al. [22]
Lifecycle carbon footprint comparison between internal combustion engine versus electric transit vehicle: A case study in the U.S.	Renewable energy and clean power generation might reduce carbon emissions by 41%.	Farzaneh and Jung [23]
Emission from Internal Combustion Engines and BEVs: Case Study for Poland	Three main factors that contribute to EV emission are the type of ICEV and its displacement, EV electric consumption and energy mix.	Zimakowska-Laskowska and P. Laskowski [24]
Comparison of total PM emissions emitted from electric and ICEVs: An experimental analysis	EVs, despite being considered zero-emission vehicles, still contribute to non-exhaust PM emissions. The study concludes that when considering both exhaust and non-exhaust emissions, the total PM emissions of EVs are generally lower than those of ICEVs.	Wu et al. [25]

3. Method: Electric Vehicles and Life Cycle Assessments

This approach is based upon existing studies about LCA and LCC of EVs. The LCC framework proposed is based on the improvements of the existing methodology presented in Figure 4. The LCC accounts for the total cost of each of the lifecycle stages, including the manufacturing, operating, and disposal phases. The LCC performed accounts for the total cost of each of the lifecycle stages, including the manufacturing, operating, and disposal phases. It consists of two components, which are social life cycle cost (SLCC) and consumer life cycle cost (CLCC). SLCC is a cost associated with vehicle environmental impacts comprised of GHG emissions and air quality emissions. CLCC is associated with the final purchase price, operating cost, time cost (time loss during maintenance), and disposal cost. Next, the total LCC for each vehicle was assessed with the combination of SLCC and CLCC. The GREET Software, developed by Argonne International Laboratory, is used to calculate the lifecycle emissions intensities of vehicles. This publicly available tool provides comprehensive data covering the entire vehicle lifecycle, from the manufacturing phase to the end-of-life phase.

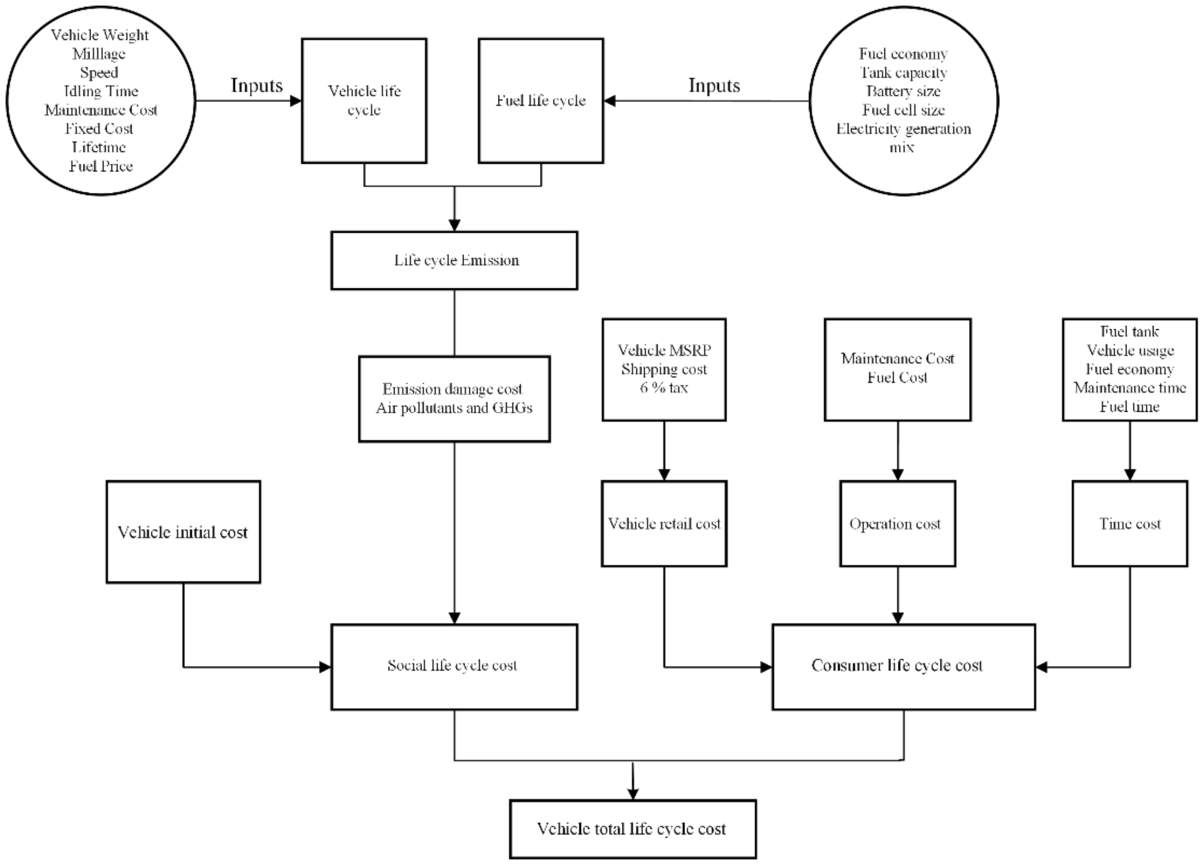


Figure 4. Life cycle cost framework (adapted from Ahmadi [7]).

In this study, HEV, BEV, PHEV, and FCEV fuelled with hydrogen was tested with gasoline-based vehicle is used as a benchmark. Thus, the most representative model was selected, i.e., Hyundai Elantra for a gasoline engine vehicle, Kia Niro for an HEV, Hyundai Kona Electric for a BEV, Hyundai Sonata for a PHEV, and Hyundai Nexo for a FCEV. A comparative study on the life cycle emissions and total LCC is conducted for every type of vehicle. For consistent and accurate results, several assumptions were made. The vehicle's standard working condition is in an urban environment, and annual and lifetime usage is the same for all types of EVs. Annual vehicular miles are assumed to be 12,000 miles with 12 years of lifetime usage [26].

The vehicle specification was obtained from the manufacturer's data source, including the manufacturer's suggested retail price (MSRP), weight, fuel economy, and tank capacity. Table 2 shows vehicle parameters of the chosen vehicle model.

Table 2. Vehicle parameters and data information [26-30]

Specifications	Unit	ICE	HEV	BEV	PHEV	FCEV
Model	-	Hyundai Elantra	Kia Niro	Hyundai Kona	Hyundai Sonata	Hyundai Nexo
Weight	lbs	3020	3071	3715	3,781	4387
Average lifetime	Years	12	12	12	12	12

Specifications	Unit	ICE	HEV	BEV	PHEV	FCEV
Average annual usage	Mile	12000	12000	12000	12000	12000
Fuel economy	MPG	31	53	120	39/99	57
Fuel price	$/gallon	3.5	3.5	0.1585	3.5/0.15	6
Fuel taxes	$/gallon	0.3	0.3	0	0.3	1.1
Shipping cost	$/lb	0.23	0.23	0.23	0.23	0.23
Tank capacity	gallon	14	11.1	N/A	14.5	6.33
Time for fueling/charging	Min	6	6	30	6	8
Maintenance frequency	times	22	20	10	20	10
MSRP	$	21700	26500	36400	33400	59300
Maintenance cost	$/mile	0.101	0.094	0.061	0.09	0.061

The vehicle's first cost includes vehicle MSRP and shipping cost. The vehicle MSRP is obtained through manufacturers, while shipping cost is associated with vehicle transportation from the manufacturer to the dealership. Vehicle retail cost includes MSRP, shipping cost, and average sales tax rate which is assumed as 6% for all types of vehicles and is represented by the equation (1).

$$\text{Final Retail Cost} = [\text{MSRP} + (\text{Shipping Cost} * \text{ Vehicle Weight})] * \text{ Tax} \quad (1)$$

The fuel price is $3.39/gallon; since PHEVs use both gasoline and electricity, 2 values are represented. The electric price is presented in $/kWh; while BEV electricity price is $0.16/gallon based on June 2022 data. For the FCEV, the price for hydrogen fuel is $6/kg-$h_2$. Next, the average fuel taxes for gasoline are $0.3/gallon, and hydrogen fuel is $1.1/gallon.

Fueling and maintenance time cost is the useful time consumed during vehicle maintenance and fueling over its lifecycle. Time loss is the productivity loss of the user. The vehicle lifetime fueling frequency is calculated based on the equation (2).

$$\text{Fueling frequency} = \frac{\text{Total VMT}}{\text{Tank capacity}\times\text{Vehicle fuel efficiency}} \left(\frac{\frac{\text{miles}}{\text{year}}\times\text{vehicle lifetime}}{\text{gallons}\times\frac{\text{miles}}{\text{gallon}}} \right) \quad (2)$$

VMT is annual vehicular miles traveled, and fuel capacity vehicles are presented in Table 2. The average time loss for users to complete fueling procedures is about 6 minutes, including entering the fuel station, waiting, paying, and fueling. The assumption of the charging events of EV users is that 18% occurred away from home while 82% occurred at home. The productivity wasted to charge an EV occurring away is about 30 minutes. The assumption that zero time is wasted for the other charging cycles [7].

Internal combustion engine vehicles and EVs both have different maintenance frequencies. Internal combustion engine maintenance focuses on oil and parts replacement, while the EV, which uses electricity, does not require frequent maintenance, and it takes approximately 2 hours to pick up and drop off the vehicle each time. It is assumed that the internal combustion engine is maintained 22 times, and the BEV is half of the HEV, as they do not have an internal combustion engine. For a FCEV, it is assumed to be 11 times throughout its life [7]. The maintenance cost is determined based on the average annual maintenance cost per vehicle mile. Next, it has been estimated that the maintenance costs of different light-duty vehicles are \$0.101/mile for ICEVs, \$0.094/mile for HEVs, \$0.09/mile for PHEVs and \$0.061/mile for BEV. BEV was assumed to have a similar maintenance cost and schedule as a FCEV. The loss of time is calculated by the product of time loss with the mean hourly wage in the U.S. of \$29.76 in 2022.

The social cost of GHG and air quality pollutants is presented in 3. There are two types of emissions were considered, GHG emissions, which are a major contributor to global warming, leading to climate change and its associated impacts on the planet. On the other hand, air quality emissions pose a significant threat to human health and ecosystems. It is essential to address both types of emissions to ensure a sustainable and healthier environment for future generations. GHG emissions are composed of CO_2, CH_4, and N_2O. The air quality emissions comprise CO, NO_x, SO_x, VOC, $PM_{2.5}$, and PM_{10}. The social cost of carbon is defined as the long-term damage costs incurred from emitting an additional unit of carbon into the atmosphere today, calculated as the net present value of the ensuing climate change impacts over a longer duration. This cost is an externality, implying it isn't covered by the individuals responsible for it but will be borne by future generations and individuals globally who will be affected by the results of climate change. Estimations of the social cost of carbon are predominantly uncertain because the expense of future climate change impacts relies not only on the amount of carbon emitted currently but also on the accumulative effects of emissions in the future. et al. [20] studied published research on estimating the social cost of carbon using meta-analysis. The estimates of the social cost of carbon vary depending on the model and assumptions used. The lower and upper-value estimates ranged from \$13.36 to \$2386.91/tCO_2, with a mean value of \$54.7/tCO_2. Considering the pure rate of time preference (PRTP) at 3% in peer-reviewed studies, the estimated social cost of carbon is equal to 30.78\$/tCO_2.

The GHG emission social cost is calculated directly from the air quality pollutants inventory and its cost per unit for GHG emissions.

$$C_{GHGs} = \sum_{i} P_j e_j \tag{3}$$

C_{GHGs} are the social cost of GHG emission in \$/mile. P_j is the emission of pollutant j in g/mile, and e_j is the external cost of pollutant j in \$/gram.

$$C_{AQ} = \sum_i P_i e_i \tag{4}$$

C_{AQ} is the social cost of air quality emission in \$/mile. P_i is the emission of pollutant i in g/mile and e_i is the external cost of pollutant i in \$/gram. The e_i is the product of GWP factors and CO_2 emissions cost in \$ per gram. The GWP factors for CH_4 and

N_2O are 30 and 273 respectively. Table 3 presents the value of other pollutants. Wang et al. [31] studied published research on estimating the social cost of carbon using meta-analysis. The estimates of the social cost of carbon vary depending on the model and assumptions used. The lower and upper value estimates is ranged from 13.36 to 2,386.91$/tCO_2$, with a mean value of 54.7$/tCO_2$. Considering the pure rate of time preference (PRTP) at 3% in peer-reviewed studies, the estimated social cost of carbon is equal to 30.78$/tCO_2$. Total vehicle emissions are presented by social lifecycle cost, including vehicle first cost, lifetime operation cost, and lifetime external cost.

Table 3. Pollutant damage cost [7]

	Pollutant	Social Cost of Carbon ($/ton)
GHG	CO_2	30
	CH_4	1020
	N_2O	8940
Air Quality	CO	6424
	$PM_{2.5}$	9750
	PM_{10}	3400
	SO_X	12500
	NO_X	18600
	VOC	155500

The metrics used in this study were based on the U.S. Customary Measurement System. Table 4 provides a detailed definition for each metric.

Table 4. Measurement metrics

Metrics	Description	Unit
Average lifetime	Vehicle lifetime from resource extraction to the end-of-life phase	Years
Average annual usage	Number of miles driven per year by a vehicle	Mile
Fuel economy	Measurement of distance traveled by a vehicle per gallon consumed	MPG
Fuel price	The cost of one gallon of fuel	$/gallon
Fuel taxes	Amount of tax levied on each gallon of fuel sold	$/gallon
Shipping cost	Cost of vehicle shipping per pound of weight	$/lb
Maintenance cost	Average cost of maintenance and service per mile driven	$/mile
Time loss	The monetized value of user productivity loss from vehicle charging and maintenance	$
Carbon damage cost	Also known as the social cost of carbon, it is an economic concept that represents the estimated economic damage that one ton of carbon dioxide emissions will have on the environment and public health over a given period.	$/ton
Lifecycle cost	Total cost of owning a vehicle over 12 years	$
	Total cost of owning and operating a vehicle over mile it is driven	$/mile

Metrics	Description	Unit
Lifecycle emission	Amount of emission produced over every mile the vehicle is driven	g/mile
Lifecycle emission and cost trade-off	Balance between the total cost of owning a vehicle (LCC) and the amount of emissions it produces over its life cycle (LCE). A cheap vehicle might produce more emissions, while a low-emissions vehicle might be more expensive. This balance is crucial in purchase decisions and in policymaking related to transportation and climate change	-

4. Result and Discussion: Electric Vehicles and Life Cycle Assessments

4.1. Life Cycle GHG Emission

The primary purpose of this study was to assess the lifecycle emission and cost of several EVs with ICEVs as a benchmark. The simulation was carried out over a 12-year period with vehicular miles traveled (VMT) of 12,000 miles/year, considering the entire lifecycle from resource extraction to end-of-life disposal. The result of the simulation is presented in Figure 5. Results confirmed that EVs have a significant impact on reducing GHG emissions in the environment. ICEV leads with the highest emissions of 417 g/mile. In contrast, FCEVs emit the lowest emission of 254 g/mile, which is almost aligned with other EVs' emissions. This reveals a decrease in GHG emissions by approximately 40% when transitioning to EVs.

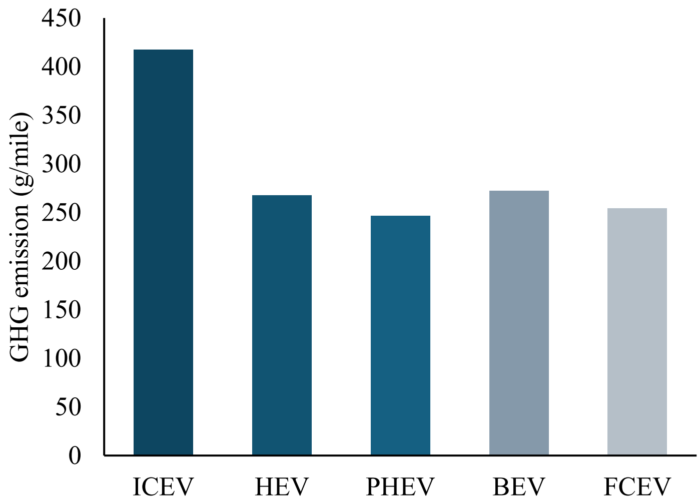


Figure 5. Life cycle GHG emission.

These findings are due to several factors. ICEVs rely on internal combustion engines that burn fossil fuel, thus contributing to the release of greenhouse gas GHG during fuel combustion. On the contrary, EVs that are powered by electricity and hydrogen produce zero tailpipe emissions during the operation phase. However, BEVs have slightly higher emissions than FCEVs due to the power generation mix in Malaysia, which relies significantly on non-renewable energy. This may relate to the PHEV emission value, which is 246 g/mile, the lowest compared to others. PHEV emissions are influenced by its charging frequency and driving ranges. With a high driving range, PHEV charging frequency will be reduced, thus resulting in lower emissions. These are aligned with studies by Xu et al. [32], which conclude that increasing driving ranges to 60 miles and reducing charging frequency can minimize GHG emissions level of PHEV.

4.2. Life Cycle Air Quality-Related Emission

The assessment of life cycle air quality-related emissions was similar to the life cycle of the GHG emissions method. The overall emissions quantity for each vehicle was demonstrated in Figure 6. It can be broken down into carbon monoxide (CO), oxides of nitrogen (NO_x), the volatile organic compound (VOC), oxides of sulfur (SO_x), and particulate matter of $PM_{2.5}$ and PM_{10}. In comparison, the ICEV has the highest value, 2 g/mile, while the FCEV has the lowest value, 0.6 g/mile. However, in terms of air quality, HEVs and PHEVs also produce high amounts of emissions, which are 1.9 g/mile and 1 g/mile, respectively. These findings can be explained by the fuel types of ICEVs, which are fully powered by gasoline, while HEV and PHEVs, which are partially powered by gasoline. This is opposed to battery and FCEVs, which utilize electricity and hydrogen as fuel sources.

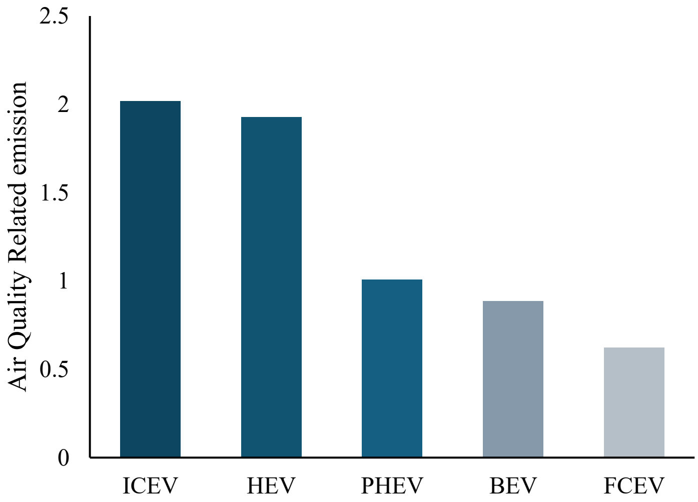


Figure 6. Air Quality Related Emission.

The quantity of CO of each vehicle is demonstrated in Figure 7. Based on the findings, an ICEV emits the most CO level with a quantity of 1.65 g/mile. This is aligned with other literature where vehicles that are operated solely by internal combustion engines tend to produce higher emissions. For HEV, the CO quantity is slightly lower than that of ICEVs, with a value of 1.63 g/mile. On the other hand, the CO emission level of FCEV is 6 times lower than ICEVs. This is due to the byproduct of hydrogen fuel production: only water. Consequently, the emission of FCEV reduced significantly.

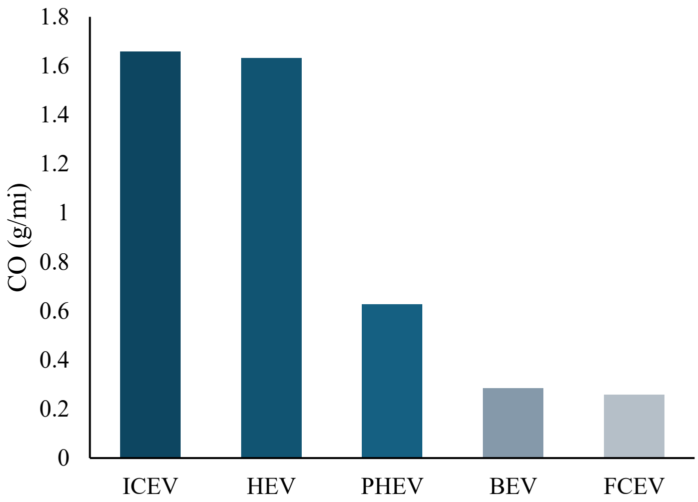


Figure 7. CO (g/mi) vs Vehicle Type.

There is a significant variation in the quantity of NO_x, as shown in Figure 8. BEV produces 0.2 g/mile, while the lowest is given by HEV. This notable difference is associated with the Malaysian electricity production mix in the well-to-pump (WTP) phase. The main contributor to electric power generation is still from non-renewable sources. NO_x gases are released through the domestic use of coal as well as exhibit corrosive properties and strong oxidizing capabilities, which is harmful to the environment [33]. Note that BEVs produce zero emissions during the operation phase.

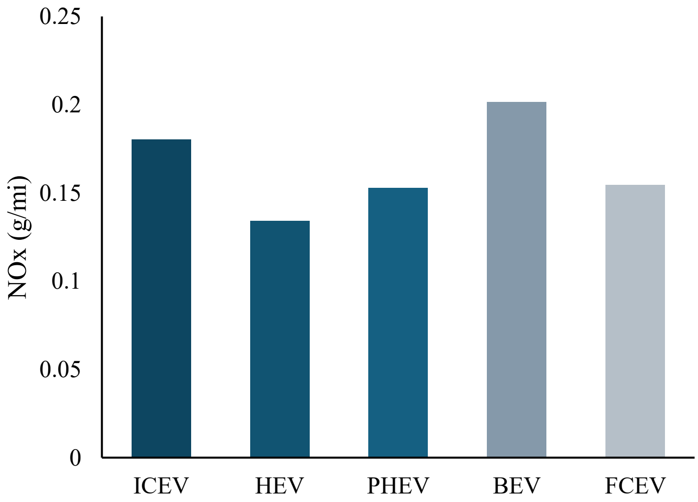


Figure 8. NOx (g/mi) VS Vehicle type.

The SO_x result for each vehicle is displayed in Figure 9. Similar to the previous graph, BEVs lead with the most SO_x emission, which is 0.32 g/mile, 3 times higher than HEV. This is primarily based on the grid electricity generation and battery production process. In the present study, BEV uses a lead-acid (Pb-Ac) battery. A study on life cycle studies of batteries by Xia and Li [20] states that nickel-metal hydride (NiMH) emits the lowest emission compared to Pb-Ac due to the high toxicity level of lead in the production process. These findings explain the lowest NOx emissions of HEV that use nickel-metal hydride (NiMH) batteries.

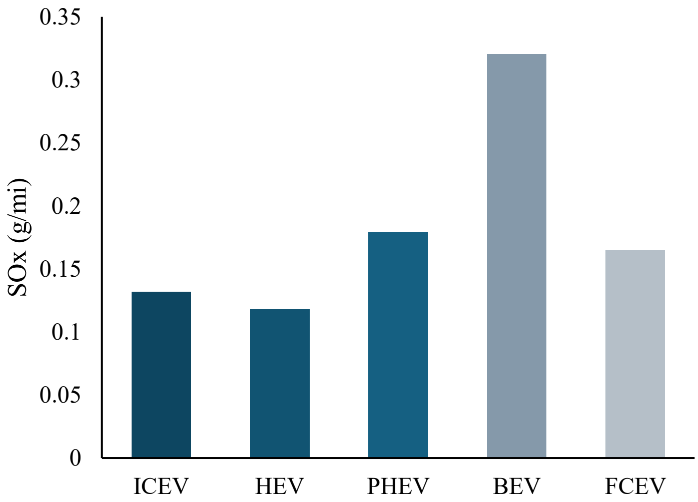


Figure 9. SOx (g/mi) VS Vehicle Type.

Moving forward, the emissions value of particulate matter (PM) is shown in Figure 10. The total PM was obtained by summating $PM_{2.5}$ and PM_{10}. PM categories are differentiated by their size. Correspondingly, the PM emission of a BEV is two times higher than that of a HEV, with 0.08 g/mile. This is also due to the electricity generation grid in Malaysia and Pb-Ac battery production.

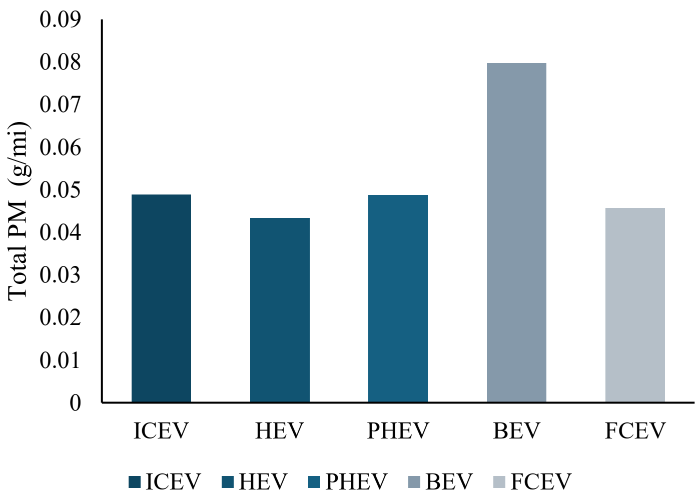


Figure 10. Total PM (g/mi) VS Vehicle type.

To summarize, the high contribution to life cycle emissions of ICEVs is influenced by vehicle and fuel usage, while EVs are determined by the electricity generation and battery production during the fuel-cycle phase. However, EVs overall still emit the lowest lifecycle emission compared to ICEVs. It is important to note that optimizing power structure for electricity generation using renewable energy, enhancing battery technology to use fewer toxic materials, and improving battery recycling to recover materials from batteries can significantly reduce emissions and pollution.

4.3. Life Cycle Cost

The LCC was designed to calculate total vehicle cost for acquisition, use, and end-of-life phases. This simulation assessed the total LCC breakdowns for ICE, HEV, PHEV, BEV, and FCEV. The total LCC was displayed in Figure 11. Firstly, the LCC results revealed that FCEV costs the highest ($155,904.40) compared to the other vehicles. This is almost two times greater than the ICEV which costs $84,584.50. However, there is a significant drop in the total life cycle cost for BEVs, with $100,6372, followed closely by PHEVs, with $96,741.80, and HEVs, with $84,857.30.

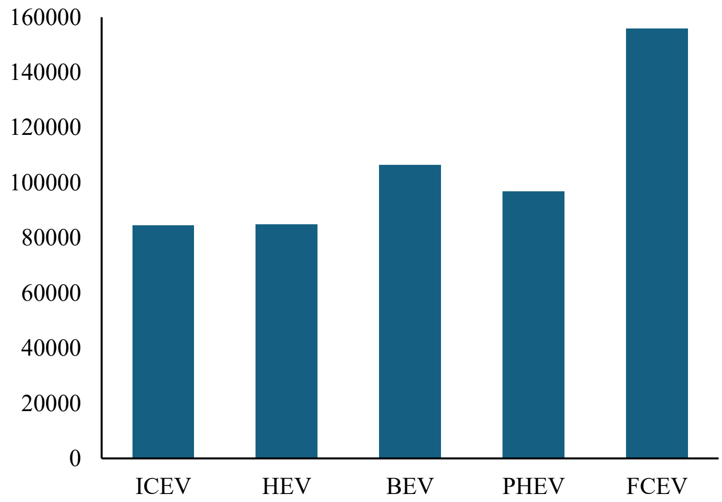


Figure 11. Total lifecycle cost VS Vehicle Type.

Maintenance time cost focuses on the temporal dimension, considering the direct and indirect expenses related to the time spent on maintenance tasks, whereas maintenance cost covers the entire financial investment in sustaining vehicles. Both indicators are essential for individuals who maximize their maintenance plans and raise their vehicles' dependability and effectiveness. When a car is purchased from a dealership, the vehicle's final retail cost comprises all associated expenditures; the vehicle's initial cost is the cost incurred at the point of acquisition, covering the purchase price and initial fees. The car's overall cost, including the manufacturer's suggested retail price (MSRP) and any additional fees levied by the dealership, is more clearly represented by the vehicle's final retail cost.

The total life cycle cost was broken down into final retail cost, GHG damage cost, air pollutant damage cost, fueling time cost, and maintenance time cost, which is considered as time loss and maintenance cost, as shown in Figure 12. The final retail cost includes the vehicle's MSRP, shipping cost, and vehicle weight. It starts with the vehicle's final retail cost: a FCEV accounts for a total of $63,927.55. This is three times greater than the cost of ICEVs, which is only $23,738.30. This is due to expensive fuel cell stacks and hydrogen storage tanks. In addition, the heavy weights of fuel cells and hydrogen tanks also contribute to the high shipping cost of FCEVs.

Next, GHG damage cost and air pollutant damage cost were combined to obtain the carbon damage cost. Based on the calculation, the ICEV stands out with the highest value, which is $3,883.40, due to its emission during the operation stage. On the other hand, a FCEV with the lowest carbon damage cost of $2,708.69 indicates that it can be considered an option to reduce environmental pollution. However, it is challenging to penetrate FCEVs in the EV market due to their high life cycle cost.

Regarding fueling time cost, BEVs and FCEVs share the top portion of the cost with $1,497.20 and $1,583.60, respectively. This is mainly due to the charging times of fuel-cell and BEVs, which require a few hours to complete, while ICEVs only need a few minutes. The time loss is also influenced by cars' driving ranges.

Furthermore, the maintenance cost is composed of maintenance frequency, cost, VMT, and average lifetime, which is assumed to be 12 years. According to the results, the ICEV produces the highest cost at $14,544.00, followed closely by hybrid and BEVs at $13,536.00 and $12,960.00. The reason for these findings is that this gasoline-powered vehicle requires frequent oil changes and other maintenance, while EVs do not require frequent maintenance. Consequently, the maintenance cost for both FCEVs and BEVs reduces significantly, with only $8,784.00 for each vehicle.

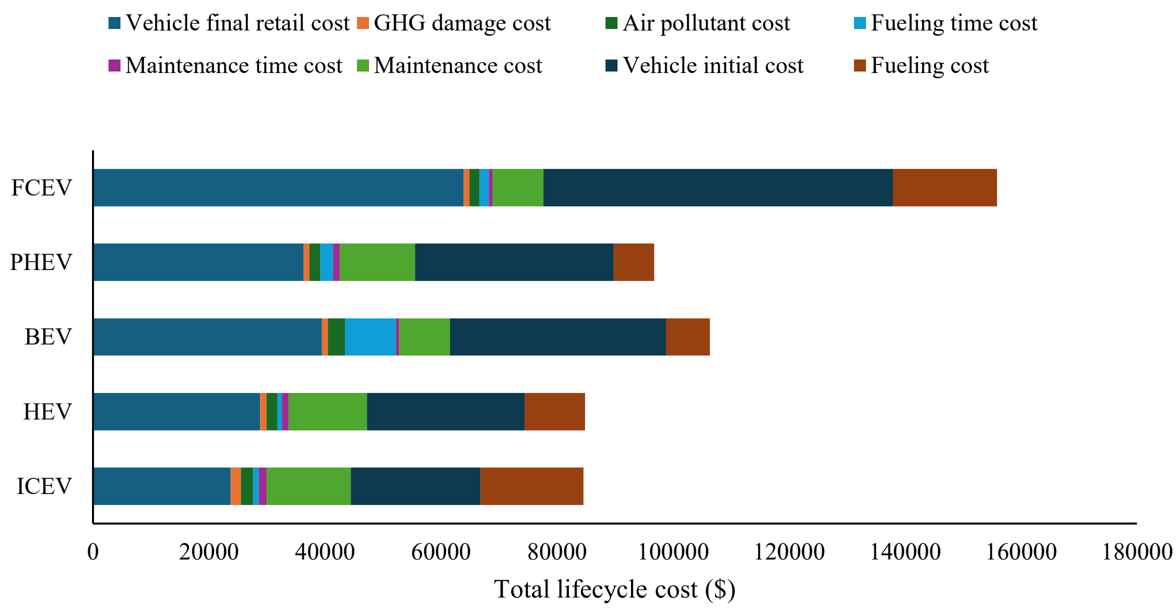


Figure 12. Total life cycle cost breakdown.

4.4. Life Cycle Emission and Cost Trade-Off

In line with the research objective to compare the lifecycle emission and cost of HEV, BEV, FCEV, and PHEV with ICEV as a benchmark, the results of life cycle emissions and lifecycle cost trade-offs are shown in Figure 13. Vehicle selection focuses solely on the emissions- and cost-based objectives. In terms of emissions, FCEV is the most viable option as it has the lowest emissions value at 254 g/mile. However, FCEV is not cost-effective due to its high cost. ICEVs have the lowest life cycle cost, with only $0.6/mile. Despite that, ICEVs produce the highest emissions level at 418 g/mile. The most environmentally friendly and cost-effective vehicle is HEV. This is due to the low production of emissions, which is 268 g/mile, and the low overall cost of $0.589/mile. Additionally, HEV has reasonable MSRP, a regenerative braking mechanism that can recover energy to generate electricity, and has longer driving ranges compared to other vehicles.

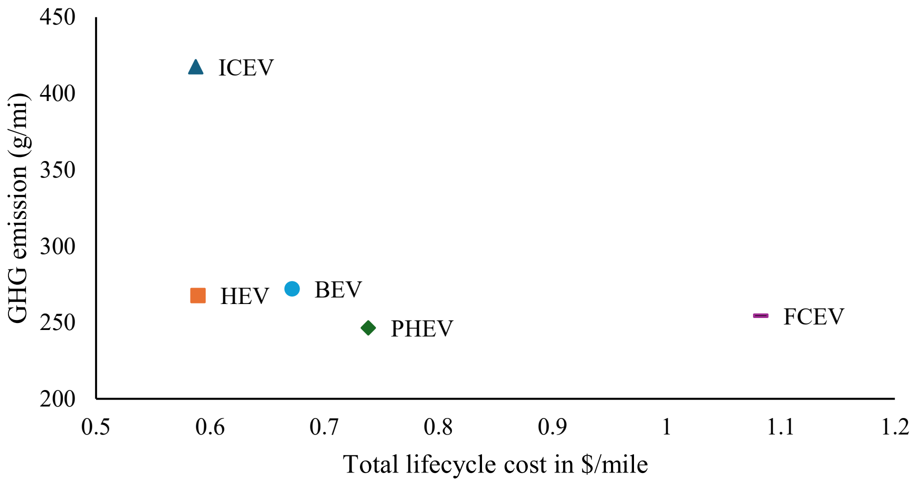


Figure 13. Lifecycle emission vs Lifecycle cost.

5. Conclusion and Recommendation

5.1. Conclusion

Overall, this study has successfully achieved the main objective: to compare each EV's life cycle cost and emissions to determine the total life cycle cost and life cycle emission. In conclusion, this research has contributed to a better understanding of vehicle life cycle emissions and cost provided valuable insights on the latest updates on EV competitiveness with ICEVs, and highlighted the underlying factors of increased emissions throughout their vehicle life.

This research project successfully addresses the research gap by comprehensively comparing life cycle emissions and costs among ICEV, BEC, HEV, PHEV, and FCEV. The study reveals that FCEV produces about half the emissions of ICEV, but EV still faces challenges in emissions like NO_x, SO_x, and PM due to battery production and electricity generation. While FCEV may currently be cost-ineffective, increasing hydrogen fueling infrastructure shows potential for cost reduction. The refined assessment points to HEV as a low-cost, low-emission option with optimal fuel economy, contributing to a better understanding of vehicle life cycle emissions and costs, offering valuable insights into EVs' competitiveness with ICEVs.

5.2. Recommendation

Based on the results and findings of this research, further studies for optimizations on electricity power grid can reduce emission during fuel-cycle phase. This includes integration of renewable energy source such as wind, hydro and solar. Energy efficiency could also reduce power loss on power generation and distribution system which leads to lower emission. On the vehicle perspective, high life cycle cost of FCEV is due to limited charging facilities, and high cost for hydrogen fueling infrastructure.

For results improvement, it includes identifying parameters, standardization of life cycle framework, clear calculation procedures and data collection method. This will refine life cycle analysis factors of EV. Thus, comparative studies on life cycle emission and cost of various EV and fuel types could be compared analytically. It is recommended to continue on this topic to help in understanding of EV economic and environmental impact and to aid in decision makers.

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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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

CRediT Authorship Contribution Statement

All authors contributed equally to the conception, analysis, writing, and final approval of the manuscript. Each author has read and agreed to the published version.

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