Alexandria Engineering Journal 82 (2023) 459–467

Contents lists available at ScienceDirect

Alexandria Engineering Journal

journal homepage: www.elsevier.com/locate/aej

Original Article

Electric vehicle (EV) and driving towards sustainability: Comparison between EV, HEV, PHEV, and ICE vehicles to achieve net zero emissions by 2050 from EV

Ibham Veza [a,*], Muhammad Zacky Asy'ari [b], M. Idris [c], Vorathin Epin [a], I.M. Rizwanul Fattah [d], Martin Spraggon [e,*]

[a] Mechanical Engineering Department, Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak, Malaysia
[b] Faculty of Engineering, Darma Persada University, Jakarta 13450, Indonesia
[c] School of Environmental Science, University of Indonesia, Jakarta 10430, Indonesia
[d] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology Sydney, Ultimo 2007, NSW, Australia
[e] Research & Innovation Center Division, Rabdan Academy, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Keywords:
Electric vehicles Indonesia
Hybrid electric vehicles
Net zero emissions 2050
Vehicle emission costs
Sustainable transportation solutions

ABSTRACT

This study explores the environmental and economic implications of Internal Combustion Engine (ICE) vehicles, Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Electric Vehicles (EVs). A case study in Indonesia is selected, focusing to achieve net zero emissions by 2050 and improve air quality. The research compares key factors such as emission costs, fueling time costs, maintenance costs, and vehicle selection for a comprehensive understanding of each vehicle type's viability in the automotive landscape. The analysis reveals that EVs exhibit the lowest CO and CO_2 emissions of about 20 %, while HEVs and PHEVs demonstrate significant reductions compared to ICE vehicles. However, EVs produce higher NOx and N_2O emissions of more than 70 %, indicating a dependence on fossil fuels for electricity generation. Air quality-related emissions, including SOx and PM10, are 90 % and 85 % higher in EVs, emphasizing the need for enhanced emission control technologies and the adoption of renewable energy sources. Despite their higher selling price and emission costs, EVs possess the lowest maintenance costs among the evaluated vehicles at only 0.00419 USD/km. Ultimately, HEVs present the most balanced combination of selling price, emission cost, and maintenance cost, making them an appealing option for the market. This study provides valuable insights for policymakers, automotive manufacturers, and consumers in transitioning towards more sustainable transportation solutions.

1. Introduction

The transportation sector is a major contributor to greenhouse gas (GHG) emissions worldwide especially internal combustion engine (ICE) vehicles [1,2]. Numerous studies [3–5] have been reported as mitigation measures to reduce air pollution. Abbas et al. [3] reported on hydroxyl gas additive in improving the combustion efficiency of gasoline engine. The results showed that CO_2, CO and NOx pollutants have been reduced by a significant amount of percentage. Recently, Har et al. [4,5] reported on biodiesel blends to reduce the air pollutants. However, the aforementioned studies only focused on gasoline engine. As the global community focuses on achieving net zero emissions by 2050 and Sustainable Development Goal 13, a significant shift towards sustainable transportation solutions, such as electric vehicles (EVs), is essential. Liu et al. [6] reported on cost of ownership comparison between ICE and EV. However, the study only focused on ownership cost and battery electric vehicle. Sinigaglia et al. [7] reported on comparison study between ICE and various types of EVs. However, the analysis mainly focused on the number of patent, logistic growth and annual growth. Farzaneh et al. [8] reported on a case study in the U.S. between Ice and EV. However, the study only focused on carbon footprint analysis. EVs have the potential to reduce GHG emissions and improve air quality, but their adoption is hindered by high upfront prices, limited charging infrastructure, range constraints, and fossil fuel electricity generation. To reach net zero emissions by 2050 and mitigate climate change, EVs must be accepted as

* Corresponding authors.
E-mail addresses: ibham.veza@utp.edu.my (I. Veza), muhammad.zacky.asyari@gmail.com (M.Z. Asy'ari), muhammad.idris21@ui.ac.id (M. Idris), vorathin.epin@utp.edu.my (V. Epin), IslamMdRizwanul.Fattah@uts.edu.au (I.M. Rizwanul Fattah), mhernandez@ra.ac.ae (M. Spraggon).

https://doi.org/10.1016/j.aej.2023.10.020
Received 30 April 2023; Received in revised form 7 September 2023; Accepted 10 October 2023
Available online 19 October 2023

Nomenclature

BEV	battery electric vehicle
EV	electric vehicle
FCEV	fuel cell electric vehicle
GAIKINDO	Gabungan Industri Kendaraan Bermotor Indonesia
GHG	greenhouse gas
HEV	hybrid electric vehicle
ICE	internal combustion engine
LCA	Life-cycle assessment
OTR	On the Road
PHEV	plug-in hybrid electric vehicle
WTW	well-to-wheel
CO_2	carbon dioxide
CO	carbon monoxide
CH_4	methane
NOx	nitrogen oxides
N_2O	nitrous oxide
SOx	sulfur oxides

a credible alternative to ICE vehicles. Governments and stakeholders can accelerate electric mobility and create a greener, more sustainable future by implementing targeted policies, investing in charging infrastructure, supporting technological advancements, and promoting renewable energy integration.

1.1. Vehicles classification: ICE and EV

Vehicles can be generally classified into conventional and electric types, known as internal combustion engine vehicles (ICEs) and electric vehicles (EVs), respectively. ICEs, powered by gasoline or Diesel engines, have been prevalent since the early 19th century. In contrast, EVs have gained significant market penetration in recent years [9,10].

EVs can be categorized into battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), depending on their energy sources and powertrains [11]. HEVs combine an ICE and an electric motor to improve fuel efficiency. These vehicles don't require charging at stations and can be classified into mild-HEV, full-HEV, and PHEV [12]. Full-HEVs, which are most popular among manufacturers, can operate independently or in combination with ICE and electric motor power, and can be further categorized into series, parallel, series–parallel, and complex full-HEVs [13–15].

BEVs, also known as "pure EVs," solely rely on electric power stored in batteries, requiring charging at stations [16]. They produce no greenhouse gas (GHG) emissions or noise pollution, but their performance is dependent on battery capacity and thermal management [17]. PHEVs use both an ICE and an electric powertrain, featuring larger battery capacities than HEVs and the ability to charge at stations. While environmentally friendly for short distances, PHEVs still generate emissions when using gasoline for longer trips [18].

FCEVs have gained attention for their zero-emission operation, powered by an electric motor and a fuel cell instead of a battery. They use hydrogen stored in specially designed tanks and have a short refueling time [19]. However, FCEVs face limitations in hydrogen infrastructure development [20–22]. Fig. 1. illustrates the differences among vehicle classifications based on energy sources, powertrain devices, and emissions.

1.2. EV benefits

Transportation emits 25 % of fossil fuel CO_2 [23,24]. The Paris Agreement has encouraged governments to cut GHG emissions, notably in transport, due to environmental concerns [25–27]. EVs have the potential to reduce fossil fuel use, GHG emissions, and climate change [28]. In 2020, there were over 10 million EVs worldwide [29]. China leads the EV business due to rising demand for eco-friendly, high-tech, and safe vehicles. EV technology has evolved for public transit, but electric automobiles have recently garnered interest [30].

Electric vehicles (EVs) have emerged as a promising solution to the negative impacts associated with internal combustion engine vehicles (ICEs) in the transportation sector. Their growing popularity can be attributed to several key advantages they offer over their ICE counterparts [31–33]. One of the most significant benefits of EVs is their environmental impact. They help reduce greenhouse gas (GHG) emissions since they produce no tailpipe emissions, contributing to improved public health [34,35]. Additionally, EVs reduce noise pollution in urban areas, as they operate more quietly than ICEs [36,37]. Furthermore, both EVs and their batteries are recyclable, addressing the increasing

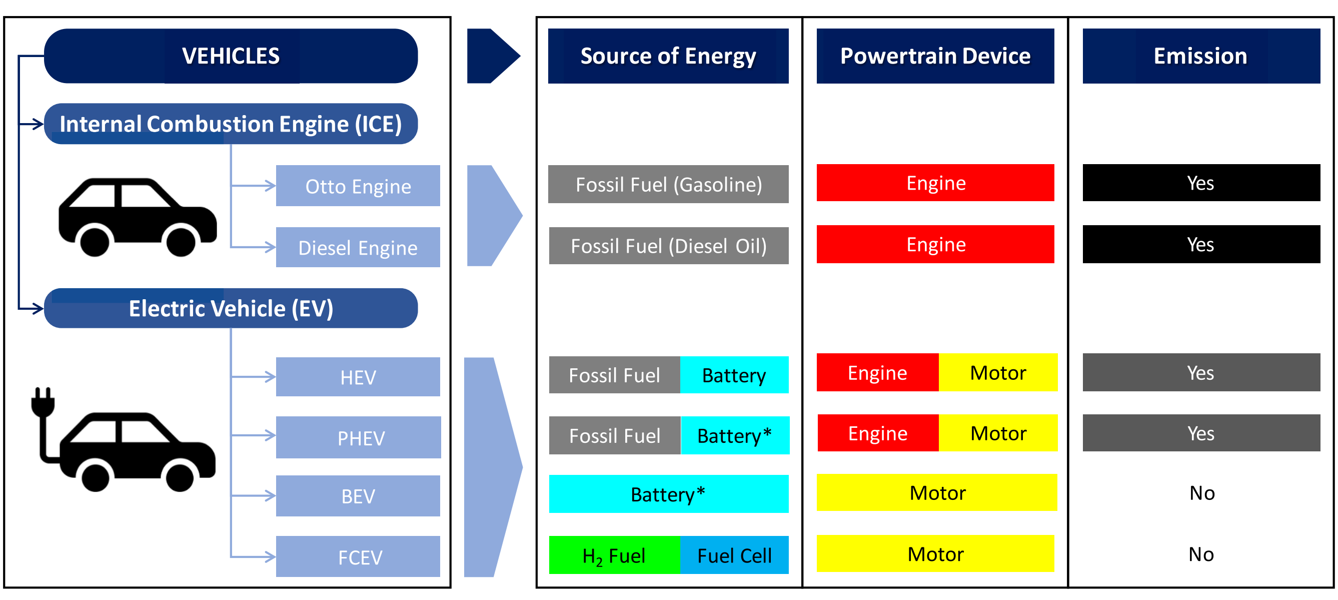


Fig. 1. Classification of Vehicle: ICE and EV.

demand for battery materials and mitigating related environmental concerns [38,39].

The construction and mechanical systems of EVs are another advantage. They feature a simpler and more compact design than ICEs, with fewer moving parts and less complex transmissions. This streamlined construction contributes to improved energy consumption, as EVs can convert up to 86 % of the battery's energy into electricity, while ICEs only utilize 20 % of the fuel's energy [40]. In terms of performance, EVs demonstrate higher well-to-wheel (WTW) efficiency than ICEs, particularly when powered by renewable energy sources [41]. They are also more reliable, responsive, and better suited for digital integration, making them attractive options for consumers [42].

Lastly, the cost aspect of EVs is noteworthy. They have lower maintenance costs due to their simple battery-electric motor systems [43,44]. The total cost of ownership for EVs can be recovered within five to eight years, depending on the vehicle's range [45]. Furthermore, EV owners can obtain additional revenues by participating in primary frequency regulation markets. Countries are striving to increase EV adoption to leverage these benefits and promote sustainable transportation. This is being achieved through providing incentives, subsidies, and expanding EV infrastructure.

1.3. Contribution of the study on the development of EV

Indonesia, Southeast Asia's most populous nation, is developing measures to reduce emissions in power generation and transportation to attain net-zero emissions and climate resilience [46]. By 2025, Indonesia plans to have 2.1 million two-wheeled and 2,200 four-wheeled EVs on the road [47,48]. Indonesia, Southeast Asia's largest vehicle market, offers huge EV market prospects while tackling ICE car air pollution.

Life-cycle assessment (LCA) is normally used to examine the environmental impact of EVs from raw material extraction to final disposal [49]. The well-to-wheel (WTW) approach is used to compare vehicle technology emissions [50–52]. From fossil fuel extraction or electricity generation to vehicle operation, the WTW analysis provides a complete picture of vehicle energy consumption and efficiency. In short, EVs can reduce transportation's environmental impact. LCA and WTW studies become increasingly important when nations like Indonesia set high EV adoption targets. Fig. 2 shows the WTW analysis comparison between ICE and EV.

This paper offers a holistic analysis of the Indonesian automotive landscape, focuses on the environmental and economic impacts of different vehicle types. This study extends beyond emission comparisons to consider fueling time, maintenance, and vehicle selection to better assess each vehicle's feasibility in Indonesia. The research helps stakeholders make informed decisions and tailor sustainable mobility solutions by highlighting the pros and cons of ICE cars, HEVs, PHEVs, and EVs in respect to the country's unique circumstances. The study also contributes to the worldwide discussion on net zero emissions by 2050 and serves as a model for other growing markets with comparable goals.

2. Methodology

To compare each type of EV, several different parameters were used such as maintenance cost, purchase cost, emission cost. For the vehicle emissions calculations, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) software developed by Argonne National Laboratory was used in this study. The GREET model can determine the effects of vehicle technologies lifecycle. Using the software, vehicle manufacturers, policy makers, regulators, and researchers are able to assess the impacts of energy and environmental of vehicle technologies. The GREET model has the capability to calculate the detailed energy consumption (including both non-renewable and renewable sources), air pollutant emissions, greenhouse gas emissions, and water consumption associated with a certain vehicle system.

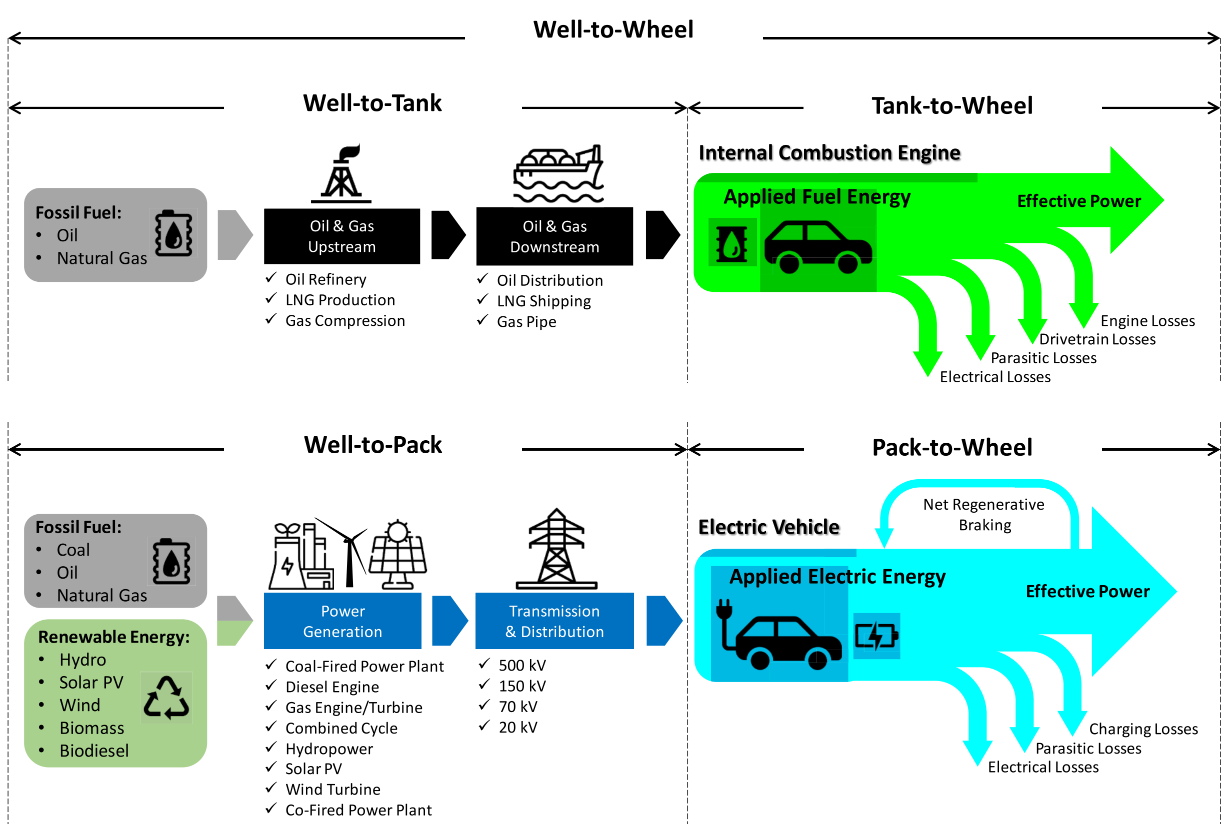


Fig. 2. The comparison of WTW analysis for ICE and EV.

2.1. Data collection for the EV

Vehicle data being used is according to *Gabungan Industri Kendaraan Bermotor Indonesia* (GAIKINDO) or The Association of Indonesia Automotive Industries. The data of car sales for every manufacturer and type of vehicle were selected between 2017 and 2021 as shown in Table 1. Note that the data of Internal Combustion Engine (ICE) vehicle is classified into two types: gasoline and diesel engine. The Toyota Innova was selected for its gasoline engine, while the Mitsubishi Pajero was chosen for its diesel engine. In the realm of electric vehicles, the Mitsubishi Outlander Sport PHEV was picked as a standout performer. Although the Toyota Corolla Cross is a relatively new entrant in the hybrid market compared to its predecessor, the Toyota Camry Hybrid, its impressive sales figures have earned it a place in this comparison. Lastly, the Hyundai Kona Electric has gained significant traction in the Indonesian market, boasting the highest sales growth for electric vehicles among its competitors.

Since hybrid vehicles use both electricity and gasoline as fuel source. Therefore, there are two numbers on the fuel price according to Table 2. While vehicle operate using electricity as a main source, it is considered electricity price as a fuel cost. On the other hand, gasoline price is preferred when the vehicle use ICE as a main power during used.

Each vehicle has a different parameter to compare, such as On the Road (OTR) price, operational cost (fuel, maintenance, and tax) and time for fueling or charging. The methodology to estimate final emission cost is collected from two aspects (Fig. 3). One aspect is for vehicle life cycle emission; the other is for fuel life cycle emission including tank capacity, fuel economy, fuel transportation and electricity generation mix. From the two aspects, the life cycle, air pollutant and social life cycle emission will be calculated using the GREET software.

Two types of gasoline are commonly used in Indonesia, RON92 and RON98 classified based on their octane number. The majority of the vehicle owners use RON92 as a preference for Toyota Innova as they have compression ratio is lower which allow to use lower RON gasoline number than that are available on PHEV. Therefore, the fuel price is also different due to the type of engine used on those vehicles. Diesel fuel type for Mitsubishi Pajero in this study has cetane number of 53, this type of fuel has the lowest sulphure contents.

The fuel price for an electric vehicle is calculated according to the equivalent number to the gasoline. One liter of gasoline contains energy equivalent to 8.9kWh of electricity [53].

The electricity mix in Indonesia is mainly based on fossil fuels like coal, natural gas, and oil. According to the study by [54], coal has the biggest contribution to Indonesia energy generation as shown in Fig. 4. It has more than 50 % of the electricity mix in the country from the coal power plant. On the other hand, electricity generated from a renewable source is not significant compared to the fossil fuel type energy generation.

Table 1
Car sales for the selected vehicle used in this study.

Vehicle Brand	Unit Sales				
	2021(until Sept)	2020	2019	2018	2017
Toyota Innova (ICE gasoline)	33,375	27,592	52,705	59,630	61,775
Mitsubishi Pajero (ICE diesel)	11,843	8,693	16,662	19,338	18,577
Toyota Corolla Cross (HEV)	1,070	652	x	x	x
Mitsubishi Outlander Sport (PHEV)	35	6	20	x	x
Hyundai Kona Electric (EV)	315	60	x	x	x

2.2. EV emission cost

In this study, it is presented that the emission cost for each vehicle to be compared. Since every vehicle has a different emission level, it is interesting to explore in terms of economic aspects besides the environmental impact. Each type of pollutant has a particular emission cost as is shown in Table 3.

The total emission cost is calculated directly from the emission type generated by each vehicle to the cost per unit as follows:

$$C = \sum_i P_i e_i \tag{1}$$

C is the total of external related pollutant cost in $ per 1000 km (Table 4). While P is pollutant *i* in g per km and *e* is emission cost *i* in $ per g.

2.3. EV fueling time cost

Every vehicle in this study has a different time for fueling. Although the EV has a longer time to charge, owners prefer to charge on their home [56]. Therefore, re-charge at a commercial charging station would be very rare. In overall for time spending in terms of productivity, EV is not frequent for the maintenance compared to the ICE. While ICE not required longer time for re-fueling.

The accessibility charging stations are crucial components of automobile ownership. In the context of ICE cars, refueling stations are readily available and widely dispersed within urban and suburban regions. The development of EV charging infrastructure is still in progress in numerous places. While the convenience of home charging is undeniable, the widespread availability of fast-charging stations plays a critical role in facilitating long-distance travel and catering to individuals who lack access to home charging facilities.

2.4. EV maintenance cost

A further aspect that taken into account is the expenses and regularity associated with vehicle maintenance. Despite the relative rarity of EV maintenance in comparison to ICE vehicles, it is necessary to further explore the underlying factors contributing to this phenomenon. EVs possess a lower number of mechanical components in comparison to ICE vehicles, thus minimizing the likelihood of mechanical degradation. Electric vehicles do not possess certain integral elements such as exhaust systems, transmissions, and oil systems, which frequently necessitate maintenance in ICE vehicles. Also, the regenerative braking in EVs has the potential to reduce the extent of wear experienced by brake systems. Throughout the duration of the vehicle's lifespan, the above characteristics have the potential to result in substantial cost reductions for owners of electric vehicles. However, it is important to identify potential obstacles that may arise, such battery degradation and the associated expenses of replacement.

The EV maintenance data is not sufficient data in Indonesia, as they are still premature in the national market, although many manufacturers claim that the EV is "zero" maintenance. The biggest concern to consider is the price of battery on EV which has a lifetime value, and the replacement cost would be very expensive. On the contrary, the ICE vehicle has frequent maintenance time whether according to the mileage or lifetime used such as oil change, filter replacements, exhaust systems, fluid change and engine tune up. The maintenance cost for each vehicle is shown on Table 2.

3. Results and discussion: EV, HEV, PHEV vs ICE

Fig. 5 shows the variation of pollutant emissions for the all the studied vehicles. From Fig. 5 (a), clearly seen that EV has the lowest CO emission which accounted for less than 0.2 g/km. Even though EVs were often seen as zero-emission vehicles, but, the battery manufacturing

Table 2
Information data of Gasoline, Diesel, HEV, PHEV and EV vehicles.

	Unit	Gasoline	Diesel	HEV	PHEV	EV
Weight	kg	1,690	1,935	1,385	1,880	2,170
passanger (5 @ 80 kg)	kg	400	400	400	400	400
Average lifetime	years	10	10	10	10	10
Average annual usage	km	10,000	10,000	10,000	10,000	10,000
Fuel economy	km/liter	10.00	11.20	23.25	56.00	51.02
Fuel price	USD/liter	0.63	0.80	0.86/0.9	0.86/0.9	0.90
Fuel taxes	USD/liter	0.03	0.04	0.04	0.04	0.05
Tank Capacity	liter	55	68	36	45	0
Time for fueling/charging	min	6	6	6	6	30
Maintenance Frequency	times	22	22	20	20	10
OTR	USD	27,934.91	41,902.37	34,918.64	62,155.18	48,886.10
Maintenance cost	USD/km	0.00851	0.01355	0.00961	0.00978	0.00419

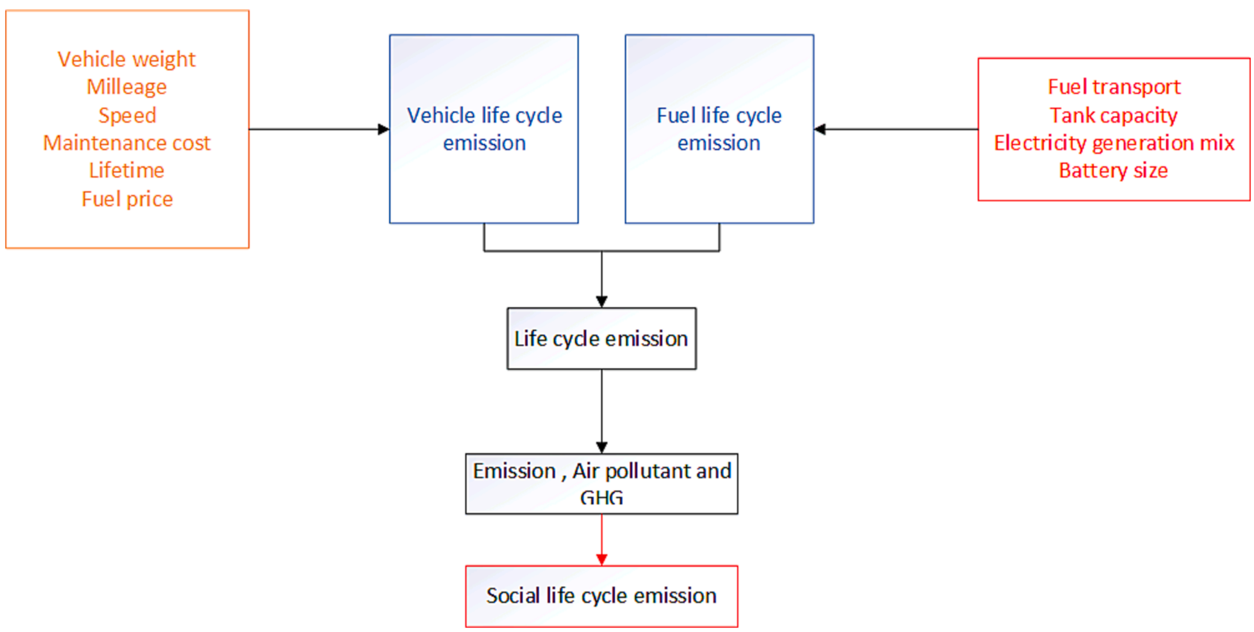


Fig. 3. Emission life cycle methodology.

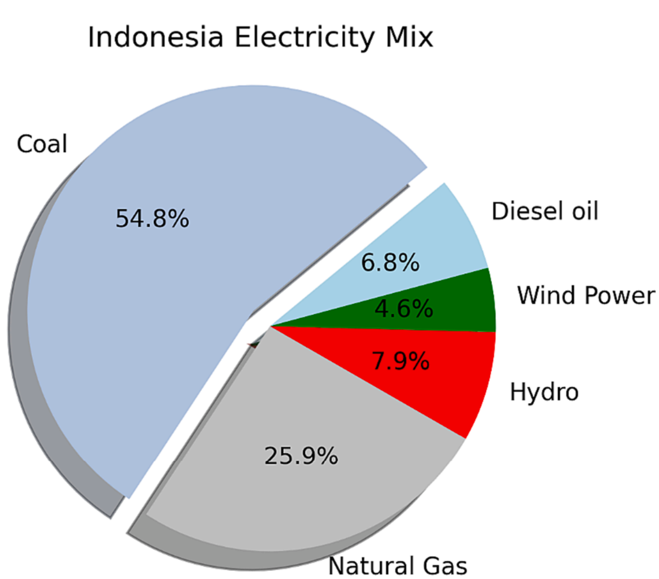


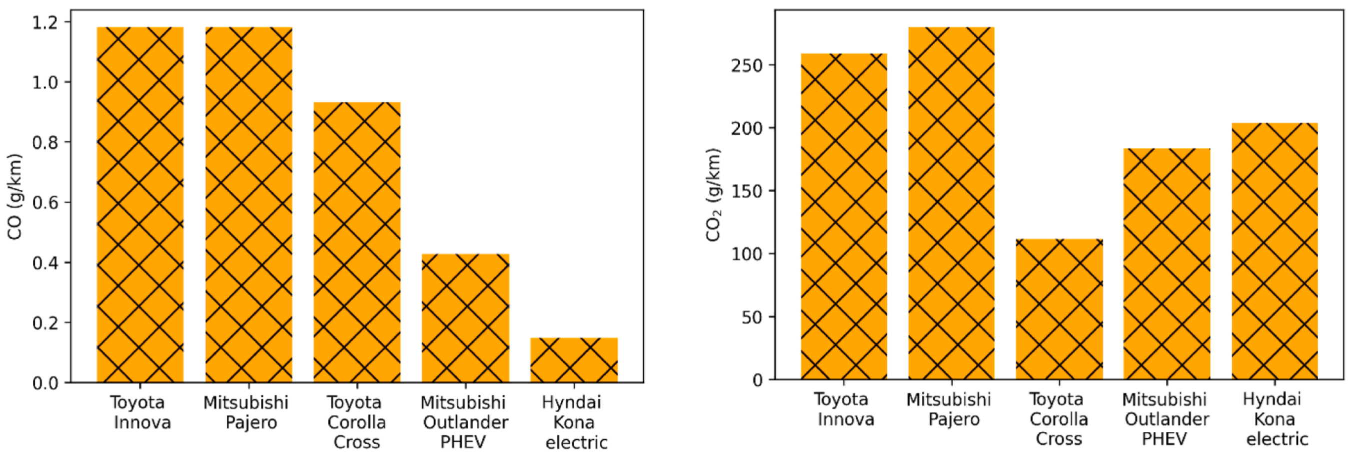
Fig. 4. Indonesian Electricity Mix.

Table 3
The emission cost of each pollutant [55].

Pollutant	Unit	Damage Cost
CO	$/kg	0.0091
NOx	$/kg	2.5716
PM10	$/kg	4.6222
PM2.5	$/kg	6.7251
SOx	$/kg	4.3267
CH_4	$/kg	0.3024
CO_2	$/kg	0.0084
N_2O	$/kg	4.3267

Table 4
Total vehicle emission cost.

Vehicle	Toyota Innova	Mitsubishi Pajero	Toyota Corolla Cross	Mitsubishi Outlander Sport	Hyundai Kona Electric
Total Damage Cost ($/1000 km)	2.6758	2.8445	1.2262	3.6652	5.0485

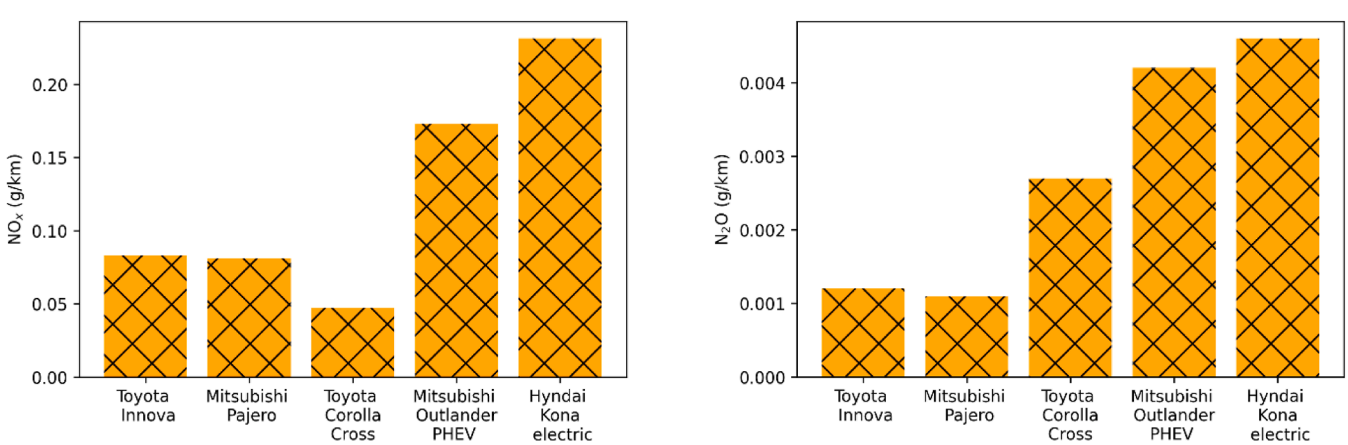


(a) (b)

Fig. 5. Variation of pollutant emissions for: (a) CO and (b) CO_2.

process do emit CO gas. The manufacturing of EVs' battery required mining of rare earth materials like lithium and cobalt which produces carbon emissions. In addition, the process of electricity generation from the power plants to charge the batteries also contributes to CO_2 emissions as shown in Fig. 5 (b). EV has lower CO_2 emissions as compared to gasoline and diesel ICEs which was about 20 % to 27 %. On the other hand, comparison between PHEV and EV shows a slight difference of less than 10 %. This can be explained as PHEV has smaller battery pack as compared to EV. However, comparison between HEV and PHEV shows huge differences of more than 30 %. This can be explained based on the working principle of both the vehicles. HEV has a small battery pack that functions to drive the vehicle only for short distances. In contrast, PHEV has a larger battery pack that works as either HEV or fully EV. PHEV will first run on fully electric and when the battery depleted, HEV operation will take over. However, due to the technology, PHEV is more expensive as compared to EV and HEV as shown in Table 2. The price of PHEV at 62,155.18 USD was 20 % and 44 % higher than EV and HEV. Out of all EVs, HEV has the cheapest OTR price, due to this it has the highest selling unit in Indonesia as shown in Table 1. From Fig. 5 (a) and Fig. 5 (b), it was observed that the carbon emissions from all the electric vehicles were much lower as compared to ICEs. Hence, EVs are the vehicle of choice in moving towards net zero emissions by 2050. A similar finding was also reported by Farzaneh et al. [8] for a case study in the U.S.

Other air pollutants from electricity generation power plants are the NOx and N_2O as shown in Fig. 6 (a) and Fig. 6 (b). Fig. 6 (a) shows that EV has the highest NOx emissions of more than 0.2 g/km. The emissions were more than half as compared to ICEs. In terms of N_2O, comparison between EV and ICEs also shows a similar trend with difference of more than 70 %. N_2O is one of the gases compounds for NOx which produced during the combustion of fuel. The reaction of N_2O with O_3 can contribute to the thinning of the ozone layer. Even worse, N_2O has a long half-life of up to 150 years. This can severely deplete the ozone layer in a long term. The high emissions of NOx and N_2O shows that the electricity power plants in Indonesia are still relying on burning of fossil fuels. The composition of CO_2 and N_2O gases also contribute to the greenhouse gas (GHG) emissions. Nevertheless, EVs are still the most environmentally friendly vehicles as compared to ICEs. HEV possessed the lowest emissions at 100.9525 g/km followed by PHEV and EV. Therefore, supporting the government's decisions in shifting to EVs as a climate change solution in Indonesia. As a suggestion, the government should create awareness regarding the benefits of EVs and continue the EV purchase



(a) (b)

Fig. 6. Variation of pollutant emissions for: (a) NOx and (b) N_2O.

subsidiary to spur sales.

Besides GHG emissions, air quality related emissions such as SOx and PM10 were also considered as shown in Fig. 7 (a) and Fig. 7 (b). The action of moving from conventional vehicles to EVs certainly will reduce air pollution. However, the emissions from the conventional power plants are something that we need to strictly consider. This is because the emissions of SOx and PM10 were 90 % and 85 % higher in EVs. From the results, it was also observed that both the pollutants increased as the size of the battery pack increases. Hyundai Kona electric, which has the biggest battery pack retrieved the highest emissions for both the pollutants. SOx and particulate matter are produced due to the combustion of fuels containing sulfur. Long term exposure to both the pollutants can lead to cardiovascular disease and respiratory related problems. Based on the results, it is suggested that emission controlling technologies should be implemented on conventional power plants. Besides, renewable energy power plants which are based on solar energy, wind energy, geothermal energy, hydropower and bioenergy can be implemented.

From the variation of pollutant emissions, it is crucial to evaluate the cost of emissions for all the vehicles, as illustrated in Fig. 8. A noteworthy observation from the data is that the high selling price of EVs is accompanied by a high emission cost. For instance, the Hyundai Kona Electric, priced at 48,886.10 USD, has the highest emission cost of 5.0485 $/1000 km.

Critical investigation of this data shows that various variables contribute to EVs' high emission cost. First, mining and processing rare earth elements like lithium and cobalt for electric vehicle batteries emits carbon. This raises EV emission costs. Second, fossil fuel-based energy generation, notably in Indonesia, produces greenhouse gases and air pollutants like NOx and SOx. This further increases the emission cost associated with EVs. Emissions also have secondary consequences like public health and environmental damage. EVs' higher emission costs, mostly owing to fossil fuel electricity generation, can harm air quality and aggravate respiratory and cardiovascular ailments. To lower electric vehicle emissions and costs, greener electricity generation methods including renewable energy sources are needed.

It is wort noting that while EVs can lower CO and CO_2 emissions compared to ICE vehicles, their high emission cost emphasises the need to evaluate the full vehicle life cycle, from manufacturing to disposal. EVs' environmental benefits and emission costs can be maximised by addressing battery production issues and switching to cleaner electrical sources.

The emission is increasing perpendicularly with respect to annual vehicle distance travel as shown in Fig. 9. Despite high selling price and emission cost, EV has the lowest maintenance cost at only 0.00419 USD/km. This is due to the low maintenance frequency of the vehicle as compared to others. Similar concluded findings were also reported by Liu et al. [6]. Overall, HEV shows good selling and emission costs as

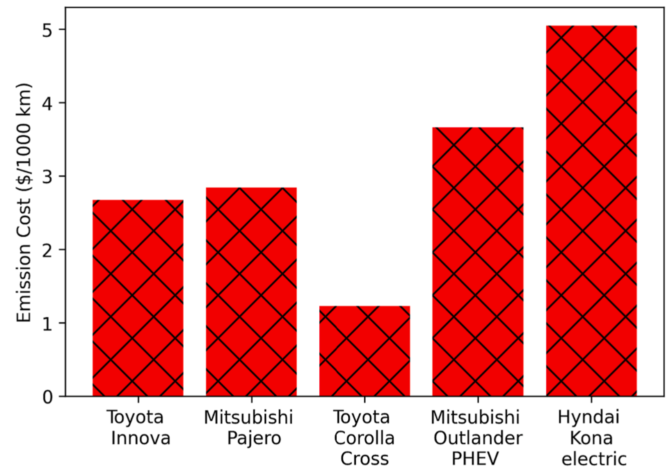


Fig. 8. Emission cost against types of vehicles.

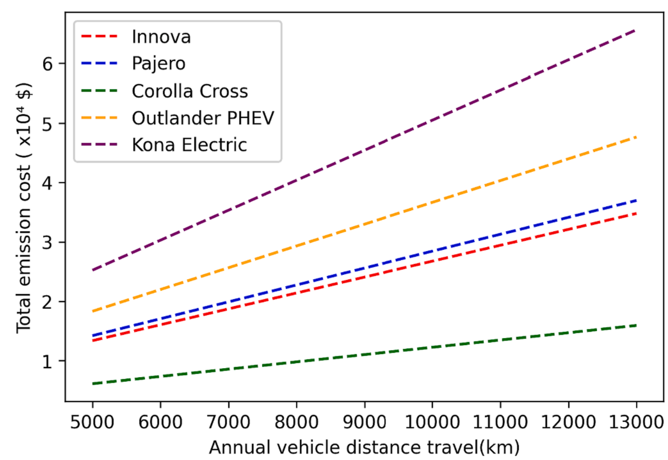
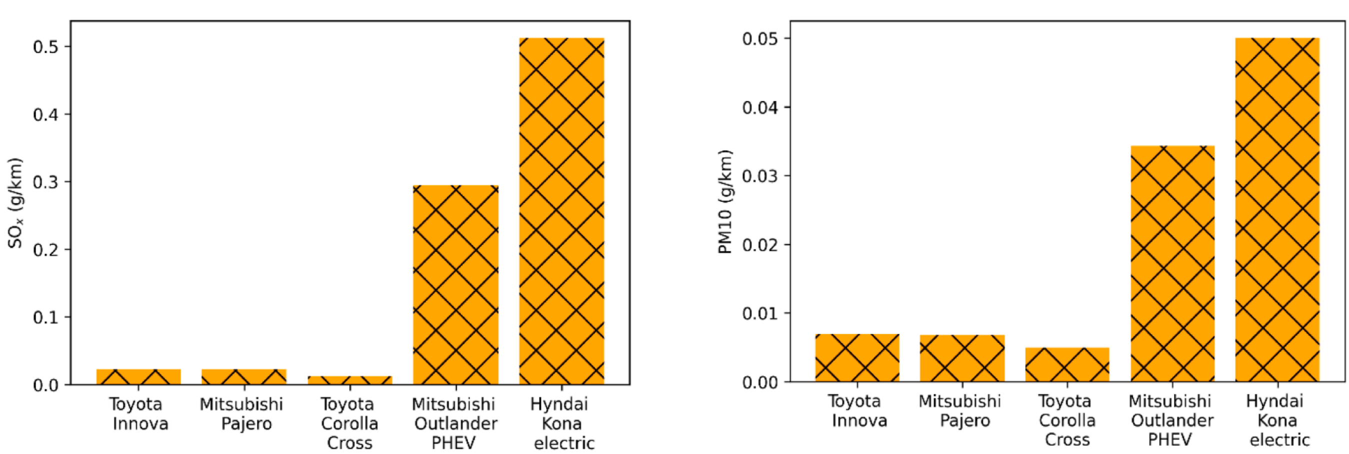


Fig. 9. Total emission cost against annual vehicle distance travel.



(a) (b)

Fig. 7. Variation of pollutant emissions for: (a) Sox and (b) PM10.

compared to all the vehicles. Both the costs at 34,918.64 USD and 1.2262 $/1000 km were the lowest of all the vehicles. These statistics truly shows that HEV is the vehicle of choice for Indonesian market. As compared to ICEs, HEV has about the same maintenance cost with the highest difference of just 0.00394 USD/km. The total emission cost of the vehicle at 13000 km mileage was 80 % lower as compared to EV. HEVs' fuel economy, regenerative braking, and electric motor-internal combustion engine synergy cut pollutants, explaining this remarkable difference.

A critical review of these findings emphasises the necessity for a thorough methodology to assessing the Indonesian market potential of different vehicle types. HEVs balance selling price, emission cost, and maintenance cost, but significant technological and infrastructure advancements could transform the scenario. Long-term improvements in battery technology, renewable energy use, and emission control could make EVs more competitive. The research reveals that HEVs are the best option for Indonesia's market, balancing economic and environmental issues. However, as technology advances, EVs and PHEVs may become more viable options.

4. Concluding remarks: What is next for EV?

In this study, we compared the environmental and economic aspects of ICE vehicles, HEVs, PHEVs, and EVs in the Indonesian market, taking into account factors such as emission costs, fueling time costs, maintenance costs, and vehicle selection, to assess their viability in achieving net zero emissions and improving air quality. From the findings of this study, several key findings and future recommendations can be drawn to provide insights into the environmental and economic implications of ICE vehicles, HEVs, PHEVs, and EVs within the Indonesian market, as well as their potential role in achieving net zero emissions and enhancing air quality.

4.1. Key findings on EV technology and ICE

- Vehicle comparison: Toyota Innova (gasoline) and Mitsubishi Pajero (diesel) were selected for ICE vehicles, Toyota Corolla Cross for HEVs, Mitsubishi Outlander Sport PHEV for PHEVs, and Hyundai Kona Electric for EVs.
- Emission cost: The Toyota Corolla Cross HEV has the lowest total damage cost per 1000 km, while the Hyundai Kona Electric has the highest.
- Fueling time cost: EVs have longer charging times, but owners often charge at home, reducing the need for commercial charging stations. In terms of overall productivity, EVs require less frequent maintenance compared to ICE vehicles.
- Maintenance cost: EV maintenance data in Indonesia is limited due to their novelty in the market. The main concern is the cost of battery replacement, while ICE vehicles have more frequent maintenance requirements (e.g., oil changes, filter replacements, exhaust systems, fluid changes, and engine tune-ups).
- EVs have the lowest CO and CO_2 emissions, while PHEVs and HEVs show significant reductions compared to ICE vehicles, making them suitable for achieving net zero emissions by 2050.
- EVs produce higher NOx and N_2O emissions, indicating a reliance on fossil fuels for electricity generation in Indonesia.
- Air quality-related emissions, such as SOx and PM10, are higher in EVs, highlighting the need for improved emission control technologies and increased adoption of renewable energy sources.
- Despite their higher selling price and emission cost, EVs have the lowest maintenance cost among the studied vehicles.
- HEVs offer the best balance between selling price, emission cost, and maintenance cost, making them an attractive choice for the Indonesian market.

4.2. Recommendation and future directions for EV technology

Based on the findings of this study, the following recommendations can be made for the future development and adoption of environmentally friendly vehicles in the Indonesian market.

- This report suggests developing and adopting ecologically friendly automobiles in Indonesia:
- Encourage HEV adoption: Given their balance between selling price, emission cost, and maintenance cost, HEVs should be promoted by incentives, tax breaks, or subsidies to consumers and producers.
- Improve EV charging infrastructure: Invest in fast-charging stations and home-charging solutions to encourage EV adoption.
- Increase sources from renewable energy sector: Solar, wind, geothermal, and hydropower are essential for EVs' environmental impact.
- Implement emission control systems in traditional power plants to reduce SOx and PM10 emissions and promote cleaner energy sources.
- Strengthen rules and policies: The government should set and enforce stronger emissions requirements for ICE vehicles and assist HEV, PHEV, and EV development and commercialization.
- Raise public awareness: Education efforts should promote greener transportation by highlighting the environmental and economic benefits of cleaner vehicle technologies.
- Develop local battery manufacturing and recycling: To reduce battery replacement costs and the environmental impact of battery manufacturing, promote local battery production and establish recycling facilities.
- Encourage research and development in cleaner vehicle technologies, energy storage systems, and renewable energy sources to increase Indonesia's sustainable transportation solutions' efficiency, performance, and affordability.

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.

References

[1] V. Srivastava, J. Schaub, S. Pischinger, Model-based closed-loop control strategies for flex-fuel capability, Appl. Energy 350 (2023), 121795.
[2] M.W. Azam, G.Q. Chaudhary, U. Sajjad, N. Abbas, W.-M. Yan, Performance investigation of solar assisted desiccant integrated Maisotsenko cycle cooler in subtropical climate conditions, Case Stud. Therm. Eng. 44 (2023), 102864.
[3] N. Abbas, M.A. Badshah, M.B. Awan, N. Zahra, Performance and gaseous emission investigation of low powered spark ignition engine fueled with gasoline and hydroxyl gas: hydroxyl gas-gasoline mixture engine, Proc. Pak. Acad. Sci.: A. Phys. Comput. Sci. 55 (1) (2018) 11–20.
[4] M.U. Haq, et al., Numerical and experimental spray analysis of castor and jatropha biodiesel under non-evaporating conditions, Energies 15 (20) (2022) 7808.
[5] M.U. Haq, A.T. Jafry, S. Ahmad, T.A. Cheema, M.Q. Ansari, N. Abbas, Recent advances in fuel additives and their spray characteristics for diesel-based blends, Energies 15(19) (2022) 7281, Available: https://www.mdpi.com/1996-1073/15/19/7281.
[6] Z. Liu, et al., Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles, Energy Policy 158 (2021), 112564.
[7] T. Sinigaglia, M.E.S. Martins, J.C.M. Siluk, Technological forecasting for fuel cell electric vehicle: a comparison with electric vehicles and internal combustion engine vehicles, World Patent Inf. 71 (2022), 102152.
[8] F. Farzaneh, S. Jung, Lifecycle carbon footprint comparison between internal combustion engine versus electric transit vehicle: a case study in the US, J. Clean. Prod. 390 (2023), 136111.
[9] D. Lavee, A. Parsha, Cost-benefit analyses of policy tools to encourage the use of Plug-in electric vehicles, Transp. Res. Interdiscip. Perspect. 11 (2021), https://doi.org/10.1016/j.trip.2021.100404.
[10] J. Dižo, et al., Electric and plug-in hybrid vehicles and their infrastructure in a particular European region, Transp. Res. Proc. 55 (2021) 629–636, https://doi.org/10.1016/j.trpro.2021.07.029.

[11] S. Andrzej, I. Pielecha, W. Cieslik, Fuel cell electric vehicle (FCEV) energy flow analysis in real driving conditions (RDC), Energies 14 (2021), https://doi.org/10.3390/en14165018.
[12] H.S. Das, C.W. Tan, A.H.M. Yatim, Fuel cell hybrid electric vehicles: a review on power conditioning units and topologies, Renew. Sustain. Energy Rev. 76 (2017) 268–291, https://doi.org/10.1016/j.rser.2017.03.056.
[13] H. Wang, W. Yang, Y. Chen, Y. Wang, Overview of Hybrid Electric Vehicle Trend, 1st ed., Vol. 1955, AIP Publishing LLC, 2018, pp. 40160.
[14] M.-K. Tran, M. Akinsanya, S. Panchal, R. Fraser, M. Fowler, Design of a hybrid electric vehicle powertrain for performance optimization considering various powertrain components and configurations, Vehicles 3 (1) (2021) 20–32.
[15] S.F. Tie, C.W. Tan, A review of energy sources and energy management system in electric vehicles, Renew. Sustain. Energy Rev. 20 (2013) 82–102, https://doi.org/10.1016/j.rser.2012.11.077.
[16] W. Li, R. Long, H. Chen, J. Geng, A review of factors influencing consumer intentions to adopt battery electric vehicles, Renew. Sustain. Energy Rev. 78 (2017) 318–328, https://doi.org/10.1016/j.rser.2017.04.076.
[17] Y. Lyu, A.R.M. Siddique, S.H. Majid, M. Biglarbegian, S.A. Gadsden, S. Mahmud, Electric vehicle battery thermal management system with thermoelectric cooling, Energy Rep. 5 (2019) 822–827, https://doi.org/10.1016/j.egyr.2019.06.016.
[18] S. Verma, et al., A comprehensive review on energy storage in hybrid electric vehicle, J. Traffic Transp. Eng. (Engl. Ed.) 8 (5) (2021) 621–637, https://doi.org/10.1016/j.jtte.2021.09.001.
[19] F. Un-Noor, P. Sanjeevikumar, L. Mihet-Popa, M. Mollah, E. Hossain, A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development, Energies 10 (2017), https://doi.org/10.3390/en10081217.
[20] P. Ahmadi, E. Kjeang, Realistic simulation of fuel economy and life cycle metrics for hydrogen fuel cell vehicles, Int. J. Energy Res. 41 (5) (2017) 714–727.
[21] P. Ahmadi, S.H. Torabi, H. Afsaneh, Y. Sadegheih, H. Ganjehsarabi, M. Ashjaee, The effects of driving patterns and PEM fuel cell degradation on the lifecycle assessment of hydrogen fuel cell vehicles, Int. J. Hydrogen Energy 45 (5) (2020) 3595–3608.
[22] S.C.A. de Almeida, R. Kruczan, Effects of drivetrain hybridization on fuel economy, performance and costs of a fuel cell hybrid electric vehicle, Int. J. Hydrogen Energy (2021), https://doi.org/10.1016/j.ijhydene.2021.09.144.
[23] A. International Energy and I. E. A. Agency, Global EV Outlook 2021: Accelerating ambitions despite the pandemic, 2021.
[24] F. Leach, G. Kalghatgi, R. Stone, P. Miles, The scope for improving the efficiency and environmental impact of internal combustion engines, Transp. Eng. 1 (2020), https://doi.org/10.1016/j.treng.2020.100005.
[25] W. Li, P. Stanula, P. Egede, S. Kara, C. Herrmann, Determining the main factors influencing the energy consumption of electric vehicles in the usage phase, Proc. CIRP 48 (2016) 352–357, https://doi.org/10.1016/j.procir.2016.03.014.
[26] Unfccc, Conference of the Parties (COP), Adoption of The Paris Agreement, Paris, 2015.
[27] H.L. van Soest, M.G.J. den Elzen, D.P. van Vuuren, Net-zero emission targets for major emitting countries consistent with the Paris Agreement, Nat. Commun. 12 (1) (2021) 1–9.
[28] N. Shaukat, et al., A survey on electric vehicle transportation within smart grid system, Renew. Sustain. Energy Rev. 81 (2018) 1329–1349, https://doi.org/10.1016/j.rser.2017.05.092.
[29] J. Du, M. Ouyang, J. Chen, Prospects for Chinese electric vehicle technologies in 2016–2020: Ambition and rationality, Energy 120 (2017) 584–596, https://doi.org/10.1016/j.energy.2016.11.114.
[30] M. Nour, J. Chaves-Ávila, G. Magdy, Á. Sánchez-Miralles, Review of positive and negative impacts of electric vehicles charging on electric power systems, Energies (2020), https://doi.org/10.3390/en13184675.
[31] Z. Thorne, L. Hughes, Evaluating the effectiveness of electric vehicle subsidies in Canada, Proc. Comput. Sci. 155 (2019) 519–526, https://doi.org/10.1016/j.procs.2019.08.072.
[32] N. Wang, L. Tang, W. Zhang, J. Guo, How to face the challenges caused by the abolishment of subsidies for electric vehicles in China? Energy 166 (2019) 359–372, https://doi.org/10.1016/j.energy.2018.10.006.
[33] S. Meisel, T. Merfeld, Economic incentives for the adoption of electric vehicles: a classification and review of e-vehicle services, Transp. Res. Part D: Transp. Environ. 65 (2018) 264–287, https://doi.org/10.1016/j.trd.2018.08.014.
[34] P.E. Abas, J. Yong, T.M.I. Mahlia, M.A. Hannan, Techno-economic analysis and environmental impact of electric vehicle, IEEE Access (2019) 1, https://doi.org/10.1109/ACCESS.2019.2929530.
[35] E. Pipitone, S. Caltabellotta, L. Occhipinti, A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context, Vol. 13, 2021.
[36] D.J. Thompson, J.D Ixon, Vehicle Noise, CRC Press, 2018, pp. 250–305.
[37] L. Steinbach, M.E. Altinsoy, Prediction of annoyance evaluations of electric vehicle noise by using artificial neural networks, Appl. Acoust. 145 (2019) 149–158, https://doi.org/10.1016/j.apacoust.2018.09.024.
[38] M. Rozman, Inductive wireless power transmission for automotive applications, 2019.
[39] Q. Qiao, F. Zhao, Z. Liu, H. Hao, Electric vehicle recycling in China: economic and environmental benefits, Resour. Conserv. Recycl. 140 (2019) 45–53, https://doi.org/10.1016/j.resconrec.2018.09.003.
[40] B. Pollet, I. Staffell, J. Shang, Current status of hybrid, battery and fuel cell electric vehicles: from electrochemistry to market prospects, Electrochim. Acta 84 (2012) 235–249, https://doi.org/10.1016/j.electacta.2012.03.172.
[41] A. Albatayneh, M.N. Assaf, D. Alterman, M. Jaradat, Comparison of the overall energy efficiency for internal combustion engine vehicles and electric vehicles, 2020, Retrieved from Environmental and Climate Technologies, ResearchGate: https://www.researchgate.net/publication/344860096_Comparison_of_the_Overall_Energy_Efficiency_for_Internal_Combustion_Engine_Vehicles_and_Electric_Vehicles.
[42] J.A. Sanguesa, V. Torres-Sanz, P. Garrido, F.J. Martinez, J.M. Marquez-Barja, A review on electric vehicles: technologies and challenges, Smart Cities 4 (1) (2021) 372–404.
[43] M.A. Delucchi, T.E. Lipman, An analysis of the retail and lifecycle cost of battery-powered electric vehicles, Transp. Res. Part D: Transp. Environ. 6 (6) (2001) 371–404.
[44] D. Bakker, Battery Electric Vehicles: Performance, CO2 Emissions, Lifecycle Costs and Advanced Battery Technology Development, Copernicus Institute University of Utrecht, 2010.
[45] Z. Liu, et al., Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles, Energy Policy 158 (2021), https://doi.org/10.1016/j.enpol.2021.112564.
[46] N. Bañol Arias, S. Hashemi, P.B. Andersen, C. Træholt, R. Romero, Assessment of economic benefits for EV owners participating in the primary frequency regulation markets, Int. J. Electr. Power Energy Syst. 120 (2020), https://doi.org/10.1016/j.ijepes.2020.105985.
[47] M.W.D. Utami, Y. Yuniaristanto, W. Sutopo, Adoption intention model of electric vehicle in Indonesia, Jurnal Optimasi Sistem Industri 19 (1) (2020) 70–81.
[48] I.C. Setiawan, Policy simulation of electricity-based vehicle utilization in Indonesia (electrified vehicle-HEV, PHEV, BEV and FCEV), Automot. Exp. 2 (1) (2019) 1–8.
[49] M.A. Ilgin, S.M. Gupta, Environmentally conscious manufacturing and product recovery (ECMPRO): a review of the state of the art, J. Environ. Manage. 91 (3) (2010) 563–591.
[50] L. Athanasopoulou, H. Bikas, P. Stavropoulos, Comparative well-to-wheel emissions assessment of internal combustion engine and battery electric vehicles, Proc. CIRP 78 (2018) 25–30, https://doi.org/10.1016/j.procir.2018.08.169.
[51] Z. Que, S. Wang, W. Li, Potential of energy saving and emission reduction of battery electric vehicles with two type of drivetrains in China, Energy Proc. 75 (2015) 2892–2897, https://doi.org/10.1016/j.egypro.2015.07.584.
[52] M.C. Pardo-Ferreira, J.C. Rubio-Romero, F.C. Galindo-Reyes, A. Lopez-Arquillos, Work-related road safety: the impact of the low noise levels produced by electric vehicles according to experienced drivers, Saf. Sci. 121 (2020) 580–588, https://doi.org/10.1016/j.ssci.2019.02.021.
[53] Energy Efficiency for transportation and alternative fuels, 2021.
[54] H. Xu, U. Lee, M. Wang, Life-cycle energy use and greenhouse gas emissions of palm fatty acid distillate derived renewable diesel, Renew. Sustain. Energy Rev. (2020).
[55] V. Pirmana, A.S. Alisjahbana, A.A. Yusuf, R. Hoekstra, A. Tukker, Environmental costs assessment for improved environmentaleconomic account for Indonesia, J. Clean. Prod. (2021).
[56] L.K. Mitropoulos, P.D. Prevedpurps, Life cycle emissions and cost model for urban light duty vehicles, Transp. Res. Part D: Transp. Environ. 41 (2015) 147–159.