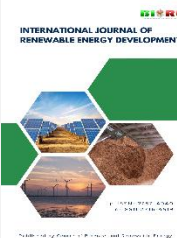




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Research Article

Environmental impact on electric vehicle: A cradle-to-cradle approach for various vehicle technologies toward sustainable transportation

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Abstract. The transition to sustainable transportation is critical to global efforts to mitigate climate change and reduce environmental degradation. Life cycle assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of various vehicle technologies throughout their entire life cycle. Numerous studies have applied cradle-to-gate, cradle-to-wheel, and cradle-to-grave approaches. However, increasing material waste from vehicles and batteries is expected to become a significant environmental challenge due to intensive mining and resource extraction activities. To address this issue, the cradle-to-cradle approach is proposed to mitigate environmental impacts during the end-of-life phase through material recycling and recovery. This study examines manufacturing, operational, and end-of-life phases across various vehicle technologies. Unlike traditional cradle-to-grave assessments, the cradle-to-cradle approach promotes resource circularity by integrating material reuse and recycling into the evaluation process, thereby minimizing waste and optimizing resource efficiency. The analysis identifies critical indicators, including energy consumption, air quality, and greenhouse gas (GHG) emissions. Although electric vehicles (EVs) significantly reduce operational emissions, they present challenges related to battery material extraction and end-of-life management. By incorporating cradle-to-cradle principles, this study highlights strategies to enhance material recovery and reusability, particularly for battery components and lightweight materials. Furthermore, this research underscores the importance of adopting renewable energy sources and circular economy principles in the transportation sector to achieve sustainability goals. Policy recommendations include strengthening recycling infrastructure, incentivizing eco-friendly vehicle design, and fostering cross-sector collaboration. The findings contribute to a deeper understanding of sustainable vehicle technology pathways and provide a framework for reducing environmental impacts while meeting growing transportation demands.

Keywords: Life cycle assessment; electric vehicle, sustainability, transportation, cradle-to-cradle



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1. Introduction

Climate change is one of the world's biggest challenges today, with far-reaching impacts on the environment, health, and the global economy (Loucks, 2021, Zhang *et al.*, 2022, Hussain and Reza, 2023). Greenhouse gas (GHG) emissions from the transportation sector are one of the main contributors to global warming, especially carbon dioxide (CO₂), produced from burning fossil fuels in conventional vehicles or internal combustion engine vehicles (ICEVs). The transportation sector accounts for about 20% of total global CO₂ emissions (Azhar *et al.*, 2024). Moreover, these emissions continue to increase in line with the rapid growth of vehicles and urbanization (Sufyanullah *et al.*, 2022). Therefore, the transportation sector is one of the top priorities in climate change mitigation efforts and requires a transition toward a more sustainable transportation system (Din *et al.*, 2023, Jelti *et al.*, 2023).

The environmental impact of conventional transportation modes is well-documented, particularly in relation to urban air

quality degradation. For example, during the COVID-19 lockdown, significant improvements in air quality were observed in major urban centers due to reduced traffic activity. A study by Progiou *et al.* (2022), demonstrated that restrictions on road, air, and marine transportation led to a reduction in emissions, with road traffic identified as the primary contributor to pollutant levels. These findings reinforce the necessity of accelerating the transition toward cleaner technologies, as part of broader efforts to reduce transport-related emissions and achieve urban air quality targets.

Low-carbon technology is essential to reduce the environmental impact of the transportation sector. Low-carbon vehicle technologies, such as high-efficiency vehicles, hybrid vehicles, full battery electric vehicles, and hydrogen-fueled vehicles, offer significant potential for lowering carbon emissions and fossil fuel consumption (Oltra and Saint Jean, 2009, Li *et al.*, 2019, García *et al.*, 2022). These vehicles help reduce tailpipe emissions from the fuel combustion process and enable the integration of renewable energy in the transportation

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sector, such as solar and wind power, to charge electric vehicles (EVs). In addition, low-carbon technologies support the global target of limiting the increase in global average temperature to below 1.5°C, in line with the Paris Agreement (Kuramochi *et al.*, 2018).

Currently, vehicle technology development is advancing rapidly, with continuous innovations in design, energy efficiency, and resources utilization (Veza *et al.*, 2021, Martyushev *et al.*, 2023, Sarma and Lindsay, 2023). EVs have gained popularity in many countries, supported by declining battery prices and increased vehicle range (Mohammadi and Saif, 2023, IEA, 2024, Khaleel *et al.*, 2024). Meanwhile, hybrid and plug-in hybrid vehicles continue to be refined as transition solutions combining conventional and electric technologies (Cao *et al.*, 2023, Guo *et al.*, 2023, Deng *et al.*, 2024). In addition, hydrogen-fueled vehicles are increasingly being introduced to the market as a promising solution for emission-free long-distance transportation (Wanniarachchi *et al.*, 2023, Hosseini, 2024, Shardeo and Sarkar, 2024).

Several life cycle assessment (LCA) studies have investigated the potential environmental impact of various EVs by comparing them to ICEV by taking into account several key variables, such as efficiency, power source, fuel source, and impact category (Qiao *et al.*, 2017, Athanasopoulou *et al.*, 2018, Kawamoto *et al.*, 2019, Shi *et al.*, 2019, Liu *et al.*, 2021, Challa *et al.*, 2022). The current LCA studies mainly focus on cradle-to-gate (the battery production stage) or cradle-to-grave (the raw material extraction to the disposal), which are the typical open-loop LCA methods (Chen *et al.*, 2022).

Numerous studies focus on investigating the carbon footprint of fuel production and exploring the potential of more environmentally friendly resources. Several studies conducted LCA using the cradle-to-gate approach. Cradle-to-gate focuses on the life cycle of a product from raw material extraction to the point at which it leaves the production facility, primarily addressing manufacturing and raw material sourcing. Kim *et al.* (2016) conducted LCA by cradle-to-gate emissions from a BEV. They assessed a mass-produced lithium-ion battery pack in the Ford. Then, Kim *et al.* (2023) continued for another type of vehicle, PHEV. Like Kim *et al.* (2016), Qiao *et al.* (2017) analyzed the BEV and compared it to the ICEV.

On the other hand, the cradle-to-wheel approach extends cradle-to-gate analysis by incorporating the vehicle usage phase. The transition from a cradle-to-gate to a cradle-to-wheel approach represents a significant improvement in sustainability practices by expanding the scope of environmental impact assessment. Cradle-to-wheel encompasses the use phase of the product by considering its operation, energy consumption, and associated emissions. Zucaro *et al.* (2016) presented an LCA of bioethanol from *perennial Arundo donax L.* feedstock. Then, Zucaro *et al.* (2018) investigated the environmental profile of bioethanol production from lignocellulosic wheat straw and its use as transportation fuel to identify the best-performing feedstock for a prospective bio-refinery network in Italy. Andersson and Börjesson (2021) presented LCA of GHG impact of current vehicle technologies (HEV, PHEV, and BEV) using a combination of electrification and renewable fuels in EU region. In China, Zhang *et al.* (2023) analyzed eleven lithium-ion battery packs composed of various selected materials by considering the battery usage phase. Veza *et al.* (2023) investigated LCA for various vehicles (ICEV, HEV, PHEV, BEV) in Indonesia.

This broader perspective enables a more comprehensive analysis of a product's environmental footprint, encouraging manufacturers to design products that are efficient to produce and sustainable throughout their operational lifetime and end-

of-life phase (disposal). In contrast to cradle-to-gate or cradle-to-wheel analysis, which covers only part of the product life cycle, the cradle-to-grave approach encompasses all stages, from raw material extraction to final disposal. Consequently, it is widely regarded as a comprehensive framework for environmental assessment. The advantages of cradle-to-grave include improved energy efficiency, reduced GHG emissions, and long-term cost savings through optimized durability, fuel efficiency, and the adoption of cleaner technologies.

In LCA research on vehicles, numerous recent studies have adopted the cradle-to-grave approach. Farzaneh and Jung (2023) and Safarian (2023) investigated ICEV and BEV life cycle emissions in the US and Sweden, respectively. In China, Fan *et al.* (2023) and Tao *et al.* (2023) assessed batteries for BEV, specifically regarding the main material of the battery. Kelly *et al.* (2022) investigated more vehicle technologies by considering all types of vehicles, such as ICEV, HEV, PHEV, BEV, and FCEV. In a related line of research, Kelly *et al.* (2024) updated their previous investigation using a cradle-to-grave approach. Most existing studies focus on the cradle-to-grave approach, which ends at disposal and overlooks opportunities for material recycling and reuse, particularly in battery components.

However, vehicle waste has become an increasing environmental problem. With advances in material recycling and remanufacturing technologies, the cradle-to-cradle approach is attracting growing attention as a sustainable alternative. Specifically, the cradle-to-cradle approach is a new full life cycle method that incorporates waste material reuse and remanufacturing. Despite the growing body of research on LCA for EVs, a notable gap remains in studies employing a cradle-to-cradle approach. This approach emphasizes not only the environmental impact across the life cycle but also the potential for resource recovery and material circularity, as demonstrated in studies by Qiao *et al.* (2019) and Chen *et al.* (2022). This gap is likely attributable to the technical complexity of modeling circular systems, which requires detailed data on material recovery rates, recycling efficiencies, and secondary material markets.

Additionally, the evolving nature of EV technologies, particularly in battery chemistry and recycling methods, introduces further uncertainty into cradle-to-cradle analyses. Addressing this gap is crucial for developing truly sustainable EV systems, particularly as Indonesia's expanding role in nickel production and battery manufacturing presents both opportunities and challenges for advancing material circularity. The present research examines how battery production can minimize environmental impact through recycling and reuse strategies. A summary of LCA studies on various vehicle technologies is presented in Table 1.

Cutting-edge research on LCA for a wide range of vehicle technologies has contributed to a deeper understanding of environmental impact across the entire life cycle of a vehicle, from raw material extraction to end-of-life. Consequently, the cradle-to-grave approach has become the primary framework for assessing the sustainability of vehicle technologies.

Based on the background and state-of-the-art literature, the primary objective of this study is to apply a cradle-to-cradle approach of various vehicle technologies, including ICEV, HEV, PHEV, BEV, and FCEV, in order to identify and compare the resulting environmental impacts throughout their life cycle. Specifically, this study aims to evaluate carbon emissions, energy use, and the ecological impact (air quality, global warming potential) across different vehicle technologies and to determine the life cycle stages with the greatest environmental impact. Through indicative profile analysis, this research seeks

Table 1
State of the arts of life-cycle assessment on vehicles

Authors	Approach	Research Location	Object	Remarks
Zucaro <i>et al.</i> (2016)	Cradle-to-Wheel	Italy	Bioethanol for ICEV	ICEV: Internal
Kim <i>et al.</i> (2016)	Cradle-to-Gate	China	ICEV, BEV	Combustion Engine
Qiao <i>et al.</i> (2017)	Cradle-to-Gate	China	ICEV, BEV	Vehicle; HEV: Hybrid
Zucaro <i>et al.</i> (2018)	Cradle-to-Wheel	Italy	Bioethanol for ICEV	Electric Vehicle; PHEV:
Qiao <i>et al.</i> (2019)	Cradle-to-Cradle	China	ICEV, BEV	Plug-in Hybrid Electric
Petrauskienė <i>et al.</i> (2020)	Cradle-to-Grave	Lithuania	ICEV, BEV	Vehicle; BEV: Battery
Andersson and Börjesson (2021)	Cradle-to-Wheel	EU	HEV, PHEV, BEV	Electric Vehicle; FCEV:
Shafique and Luo (2022)	Cradle-to-Grave	10 Countries	BEV	Fuel Cell Electric Vehicle;
Chen <i>et al.</i> (2022)	Cradle-to-Cradle	China	Battery for BEV (NCM)	NCM: Nickel Manganese
Kim <i>et al.</i> (2023)	Cradle-to-Gate	US	ICEV, BEV	Cobalt; LFP: lithium iron
Fan <i>et al.</i> (2023)	Cradle-to-Grave	China	Battery for BEV (LFP, NCM, Lead acid)	phosphate
Tao <i>et al.</i> (2023)	Cradle-to-Grave	China	Battery for BEV (ternary lithium-ion)	
Zhang <i>et al.</i> (2023)	Cradle-to-Wheel	China	Battery for BEV (11 types of LIB)	
Kelly <i>et al.</i> (2022)	Cradle-to-Grave	US	ICEV, HEV, PHEV, BEV, FCEV	
Farzaneh and Jung (2023)	Cradle-to-Grave	US	ICEV, BEV	
Safarian (2023)	Cradle-to-Grave	Sweden	ICEV, BEV	
Rashid and Pagone (2023)	Cradle-to-Grave	China	HEV, PHEV	
Veza <i>et al.</i> (2023)	Cradle-to-Wheel	Indonesia	ICEV, HEV, BEV, PHEV	
Abraham and AbdulNour (2024)	Cradle-to-Grave	US	ICEV, BEV	
Kelly <i>et al.</i> (2024)	Cradle-to-Grave	US	ICEV, HEV, PHEV, BEV, FCEV	
Present study	Cradle-to-Cradle	Indonesia	ICEV, HEV, PHEV, BEV, FCEV	

to provide evidence-based recommendations for the development of more sustainable vehicle technologies and to support low-carbon transportation policies aligned with climate change mitigation efforts.

2. Method and Data

2.1 Methodology

Life cycle assessment is an established and evolving technique for investigating the potential environmental impact of products, processes, and activities throughout their entire life cycle (Curran, 2013). Environmental impacts at the production

stage dominate some products (Bianco *et al.*, 2021), utilization (Athanasopoulou *et al.*, 2018, Kawamoto *et al.*, 2019, Challa *et al.*, 2022), and disposal (Shafique and Luo, 2022). LCA is designed to quantify and analyze the flow of materials and energy across each phase of a product's life, along with associated emissions and waste released into the environment. Identifying environmental factors throughout the life cycle is a complex process. Therefore, a systematic and robust analytical tool is required to assess the environmental performance of the vehicle system.

The LCA process is structured into several key steps to ensure a systematic and comprehensive evaluation in

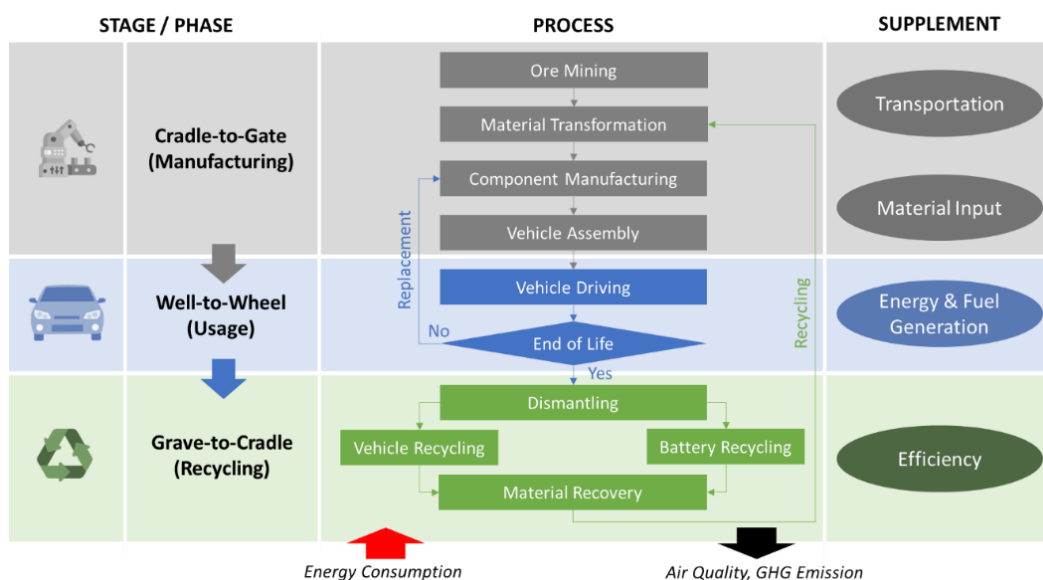


Fig. 1 Cradle-to-cradle framework for vehicles, adapted from Qiao *et al.* (2019)

accordance with ISO 14040. To ensure that a product effectively reduces GHG emissions without causing adverse environmental impacts, it is important to conduct a systematic, scenario-based environmental evaluation before large-scale adoption. The cradle-to-grave approach evaluates the potential environmental impacts associated with various vehicle technologies by examining each stage of the life cycle, from raw material extraction to final disposal, thereby providing a comprehensive assessment of a vehicle's environmental footprint.

The cradle-to-grave framework illustrated in Figure 1 provides a comprehensive LCA of a vehicle by encompassing its manufacturing, use, and end-of-life phases. The framework is divided into three primary stages: cradle-to-gate (manufacturing), well-to-wheel (use), and grave-to-cradle (recycling). Each stage represents different life cycle aspects of the vehicle and details the associated energy consumption and GHG emissions.

The cradle-to-gate phase encompasses the manufacturing process, beginning with raw material extraction (ore mining) and including material processing, component manufacturing, and final vehicle assembly. This stage requires significant energy and material input and involves transportation logistics, thereby contributing significantly to the environmental impact. The energy consumed and GHG emissions during this stage are primarily associated with material sourcing and production processes.

The well-to-wheel phase represents the vehicle's operational life cycle, focusing on driving activities and fuel or energy use. As illustrated in the flowchart, the vehicle enters a "replacement" decision point, at which it either continues operation or reaches its end-of-life stages. This phase is characterized by energy consumption from fuel or electricity, depending on the vehicle type, as well as associated GHG emissions resulting from regular use. Additional environmental

impacts arise from energy and fuel generation, which further contribute to the vehicle's environmental footprint during operation.

In the grave-to-cradle phase, vehicles undergo dismantling and recycling processes, including vehicle and battery recycling, to enable material recovery. Recycling reduces the demand for virgin materials, thereby lowering the environmental burden. Material recovery decreases both energy consumption and GHG emissions, supporting life cycle circularity by reintegrating reclaimed materials into the manufacturing process. Within the broader life cycle framework, energy consumption and GHG emission indicators are used to assess environmental impacts at each stage, providing insights into the overall sustainability of vehicle technologies. The inclusion of supplementary factors, such as transportation, material input, energy/fuel generation, and efficiency, further strengthens the LCA by identifying areas for improvement and potential reduction in environmental impact. This framework enables a holistic approach to a vehicle's environmental footprint while promoting recycling and efficient resource utilization. GREET database was employed as the primary source of life cycle inventory data, and calculations were performed using GREET software. The analysis evaluated total energy consumption, air pollutants including volatile organic compounds (VOCs), particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), and carbon monoxide (CO), GHG emissions, such as methane (CH₄), carbon dioxides (CO₂), dinitrogen oxides (N₂O), and their associated global warming potential.

2.2 Data and Material

Previous studies indicate that vehicle model specification constitutes a fundamental assumption in LCA and significantly influences the results. As this study aims to reflect real-world

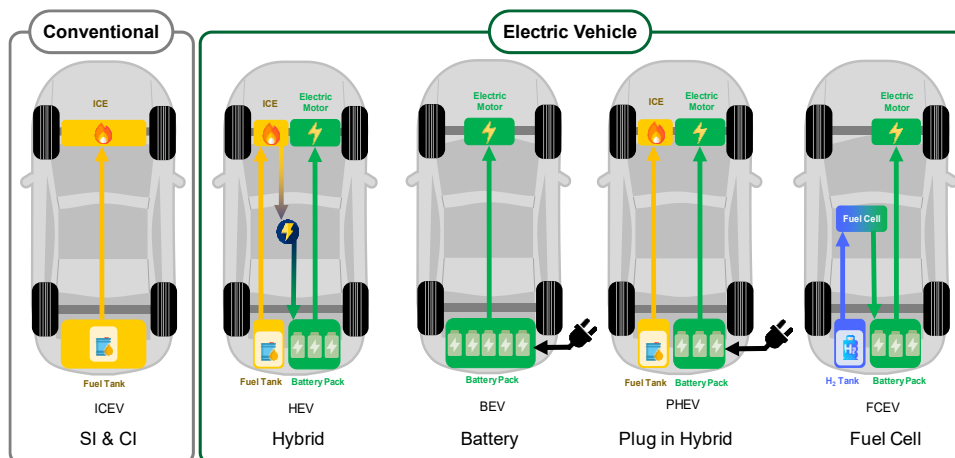


Fig. 2 Typology of vehicle technology: Internal combustion engine (SI and CI), hybrid, battery, plug-in hybrid, and fuel cell electric vehicle

Table 2
Vehicle system composition

System of Vehicle	ICEV-SI	ICEV-CI	HEV	PHEV	BEV	FCEV
Body system	☑	☑	☑	☑	☑	☑
Powertrain system	☑	☑	☑	☑	☑	☑
Transmission system	☑	☑	☑	☑	☑	☑
Chassis system	☑	☑	☑	☑	☑	☑
Traction motor	☒	☒	☑	☑	☑	☑
Generator	☒	☒	☑	☑	☒	☒
Electronic controller	☒	☒	☑	☑	☑	☑
Fuel cell auxiliary system	☒	☒	☒	☒	☒	☑

☑: Yes, ☒: None

Table 3
Data and assumptions

Parameter	Vehicle Type					
	ICEV-SI	ICEV-CI	HEV	PHEV	BEV	FCEV
VKT (km)	250,000	250,000	250,000	250,000	250,000	250,000
Curb weight (kg)	1,352.92	1,643.48	1,643.48	1,502.74	1,938.58	1,648.02
Chassis (kg)	344.99	442.10	354.99	321.59	469.14	387.28
Transmission system (kg)	85.23	96.97	82.17	75.14	108.56	46.14
Vehicle body (kg)	715.69	867.76	737.92	670.22	978.98	804.23
Powertrain system (kg)	207.00	236.66	369.78	345.63	87.24	136.79
Electronic controller (kg)	-	-	29.58	27.05	114.38	60.98
Traction motor (kg)	-	-	34.51	31.56	180.29	69.22
Generator (kg)	-	-	34.51	31.56	-	-
Fuel cell onboard storage (kg)	-	-	-	-	-	143.38
Engine oil (kg)	4.5	5	5	5	-	-
Engine coolant (kg)	11.5	15	15	15	15	15
Transmission fluid (kg)	12	16	16	16	16	16
Brake fluid (kg)	1	1	1	1	1	1
Power steering fluid (kg)	1	1	1	1	1	1
Tire (kg)	15.31	15.31	15.31	15.31	15.31	15.31
Battery (kg) – lead acid	10	10	10	10	10	10
Battery (kg) – Li-ion	-	-	45.37	154	482.40	72.59

conditions in Indonesia, the selected vehicle models are designed to align with the domestic EV market. However, specific vehicle brands are not identified for each technology. Instead, representative vehicle types are adopted for each category, including ICEV (compression ignition and spark ignition), HEV, PHEV, BEV, and FCEV, as illustrated in Figure 2.

The development of EV technologies in Indonesia has progressed in alignment with global trends, with adoption advancing gradually under the influence of government policies. As of April 2024, the number of registered EVs reached approximately 23,000 units. Between 2019 and 2024, the most prevalent EV category was passenger cars (primarily compact models with curb weights ranging from 1500 to 1900 kg). Vehicle curb weight data provided by the manufacturer were converted into the weight of the vehicle's component based on the methodology proposed by Kelly and Winjobi (2020). The contribution of material components to total vehicle mass was categorized into the powertrain system, transmission system, chassis, traction motor, generator, electronic controller, fuel cell auxiliary system, and body system, as presented in Table 2. Each vehicle technology was mapped to its corresponding component configuration. ICEV-SI and ICEV-CI were assumed to have similar structural characteristics.

Previous studies have applied different lifetime driving distances, expressed as vehicle kilometers traveled (VKT), as listed by Nordelöf *et al.* (2014), ranging from 100,000 to 260,000 km. Safarian (2023) adopted 240,000 km for the functional unit of the system. Accordingly, this study assumes that both ICEV

and EV can operate for up to 250,000 km as the baseline (long-range mileage). To examine the potential deviation resulting from lower driving distances, a sensitivity analysis was conducted using alternative mileage scenarios of 100,000, 150,000, and 200,000 km. A detailed assumption of this study is presented in Table 3.

Electric vehicles rely fundamentally on the electricity grid as their primary power source for battery charging. Consequently, the energy sources utilized in the electricity grid significantly influence the environmental impact associated with EV use. LCA studies on EVs have produced varying results regarding these vehicles' life cycle CO₂ emissions. Figure 3 illustrates the growth of total power generation capacity in Indonesia from 2010 to 2023. Fossil-based power plants dominated the mix throughout the year. Coal-fired power plants (CFPP) appeared dominant throughout the period, followed by gas-based (GFPP) and oil-based plants (DPP). Overall, fossil fuel power plants accounted for approximately 85-90%, with CFPP contributing 54% in 2023. Accordingly, the year 2023 is adopted as the baseline of the analysis.

3. Result and Discussion

3.1 Energy Consumption

Figure 4 illustrates the total energy consumption of different vehicle technologies, expressed in MJ/km. The energy consumption is categorized into two categories: fossil fuels and renewable energy. ICEV-SI and ICEV-CI show the highest total energy consumption levels among all vehicle types, with ICEV-

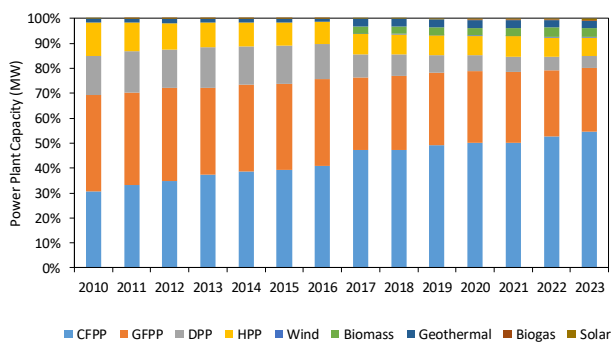


Fig. 3 Mix energy of power generation by generation type

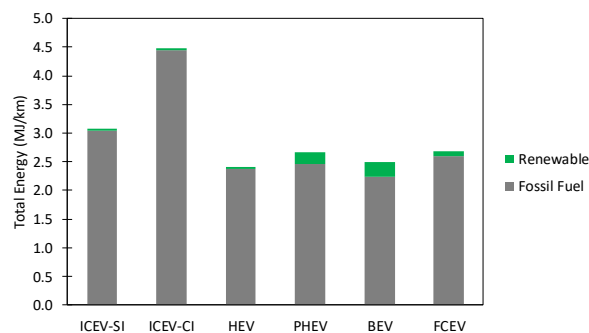


Fig. 4 Comparison of total energy consumption in MJ/km for each type of vehicle

CI showing the greatest consumption. These technologies rely almost entirely on fossil fuels, reflecting their strong traditional fuel dependency.

From a life cycle perspective, ICEV exhibits the highest total energy consumption among all vehicle technologies due to the energy-intensive of production, operation, and disposal processes. ICEV relies entirely on fossil fuels such as gasoline and diesel, which require a lot of energy for extraction processes (petroleum drilling), transportation, and refining. This process contributes significantly to their energy footprint. In addition, fossil fuels have low efficiency when converted into mechanical energy in combustion engines, thus increasing total life cycle energy requirements. During the operational phase, ICEV burns fuel to generate mechanical power.

However, engine efficiency only ranges from 20–40%, meaning that a substantial proportion of fuel energy is lost as heat. This low conversion efficiency significantly increases energy consumption over the life cycle of the vehicle. In addition, ICEVs tend to require more fuel per kilometer than other vehicles. Over extended operating periods, this accumulated fuel consumption leads to substantially higher total life cycle energy use. These findings are consistent with those of Onat *et al.* (2015), who compared ICEV-SI, HEV, PHEV, and BEV. Onat *et al.* (2015) found that ICEV and HEV had the highest and lowest total energy consumption, respectively. However, their study did not compare to ICEV-CI, which has a higher total energy consumption than ICEV-SI. This result is also supported by Peng *et al.* (2023), who found that BEV consume less energy than ICEV and PHEV, although Peng *et al.* (2023) did not compare it with HEV.

Electric vehicles (HEV, PHEV, BEV, and FCEV) display significantly lower total energy consumption than ICEV. Among these technologies, renewable energy contributions are more evident. In particular, PHEV and BEV demonstrate a more balanced energy profile, with a noticeable portion of their energy derived from renewable sources. This indicates the potential for reduced fossil fuel dependence in electrified vehicle technologies.

Although FCEV consumes less fossil fuel energy than ICEV, it still shows reliance on fossil energy, with only a small portion of renewable energy. Consequently, transitioning to HEV, PHEV, BEV, and FCEV can substantially reduce fossil fuel consumption, with BEV showing the most potential for renewable energy integration. Nevertheless, further efforts to increase renewable energy utilization across all vehicle technologies remain critical for achieving sustainable energy consumption.

3.2 Air Quality

Air quality is a critical factor in environmental health and human well-being, influenced by several pollutants, including VOC, PM, SO_x, NO_x, and CO. Potential environmental impact based on life cycle has been carried out. The result describes the potential air pollution produced by each type of EVs and compares it with conventional vehicles. As illustrated in Figure 5, the findings indicate that EVs exhibit varying air pollution impacts depending on the specific technology and energy sources utilized.

Although EVs produce little to no direct emissions during operation, producing batteries and generating electricity for recharging can result in significant air pollution, particularly when the electricity is sourced from fossil fuels such as coal. While battery technology eliminates tailpipe emissions, charging activities still contributes to a carbon footprint during

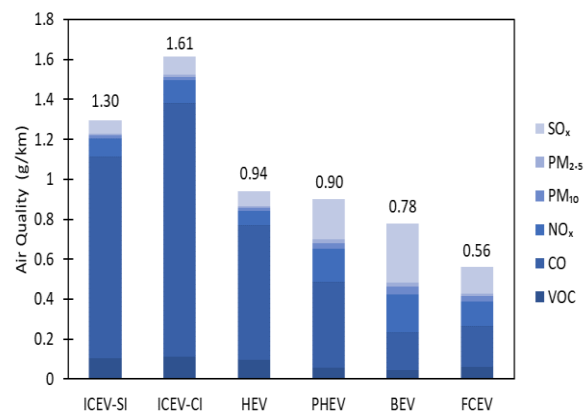


Fig. 5 Comparison of air quality values in g/km for each type of vehicle in the life cycle

the use phase. In addition, the production phase is a significant source of emissions, underscoring the importance of incorporating recycling processes to mitigate the environmental impacts across the life cycle (Aichberger and Jungmeier, 2020). Conversely, if the electricity used for EVs is generated from renewable energy sources, such as wind or solar power, associated air pollution can be drastically reduced. Therefore, the impact of air pollution on EVs is highly dependent on the type of battery technology employed and the cleanliness of the regional electricity grid.

For detail profile of air pollutants for each technology, Figure 6 shows the highest levels of each pollutant for each vehicle technology. Figure 6(a) illustrates various vehicle technologies' VOC emissions, measured in g/km. ICEV-CI exhibits the highest VOC, at approximately 0.11 g/km. HEV also exhibits relatively high VOC, though slightly lower than those of ICEVs. PHEV demonstrates a more significant reduction in VOC emissions, followed by BEV, which emits around 0.04 g/km. FCEV exhibits the lowest VOC emissions among the technologies studied. Similarly, Yang *et al.* (2021) compared ICEV, BEV, and PHEV, finding that BEV has the lowest VOC among these categories. The results of this study align with Yang *et al.* (2021) in showing that BEV have lower VOC values than ICEV and PHEV, though with differing magnitudes due to variations in assumptions and data reference. This profile is also consistent with Uğurlu (2023), who compared ICEV and BEV under various national or regional conditions worldwide. However, this study found that FCEV exhibits lower VOC than BEV.

Conventional vehicles show higher VOC due to several key factors related to the operation of internal combustion engines (ICE) and the characteristics of the fuels. Engines in conventional vehicles often fail to achieve complete fuel combustion. This incomplete combustion releases unburned organic compounds, including VOC, through the exhaust system. Moreover, gasoline and diesel fuels contain VOC that can contribute to emissions. During combustion, some of these compounds remain unburned, leading to VOC. In addition to combustion, VOC can also be released into the atmosphere through fuel evaporation, particularly during refueling or due to leaks in the fuel system. Furthermore, derated engines or those that are poorly maintained, often exhibit lower combustion efficiency, increasing the likelihood of VOC. These factors collectively make ICEV significant contributors to VOC, with adverse impacts on air quality and human health (Soni *et al.*, 2018).

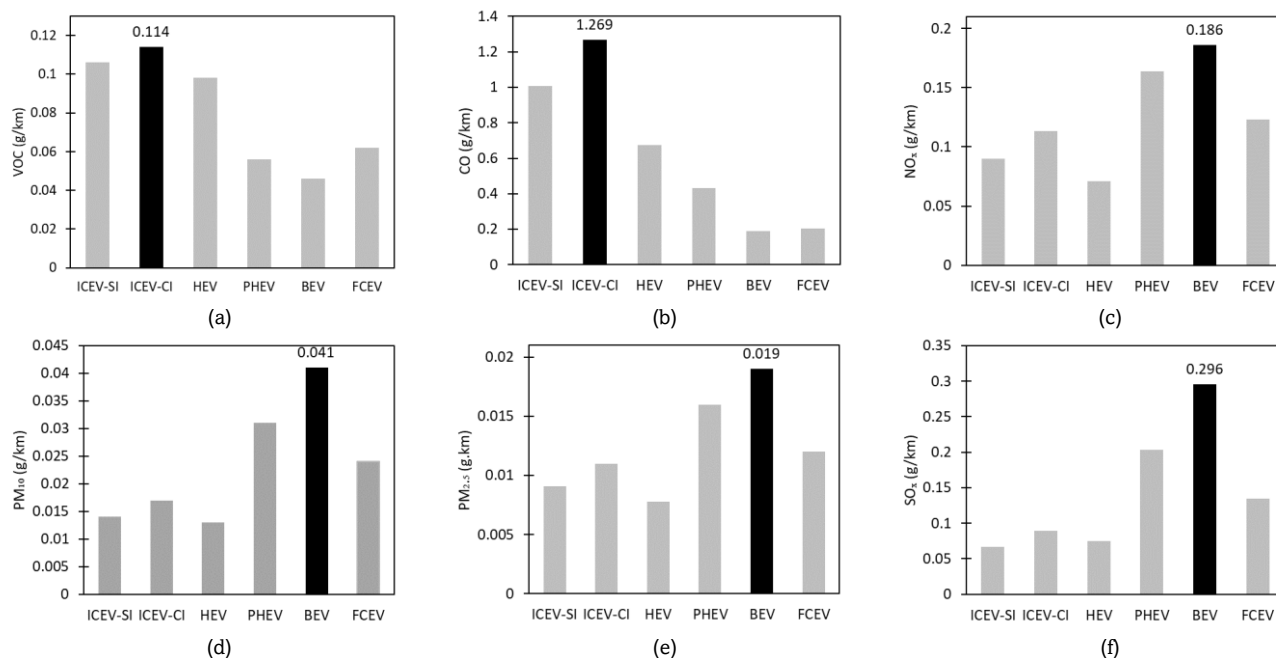


Fig. 6 Profile comparison of air pollution in g/km for each type of vehicle: (a) Volatile Organic Compounds; (b) Carbon Monoxide; (c) Nitrogen Oxides; (d) Particulate Matter 10; (e) Particulate Matter 2.5; (f) Sulfur Oxides

Regarding the CO parameter, it has a similar profile to VOC. Figure 6(b) presents the distinct CO, providing insights into the environmental impact associated with each technology. This also highlights the varying environmental performance of different vehicle technologies. ICEV-SI exhibits relatively high CO emissions, approximately 1 g/km. ICEV-SI generates significant CO emissions due to incomplete combustion. The high CO is attributed to the inherent nature of combustion in gasoline engines, particularly if the engine is poorly maintained or if the fuel used does not meet the required standards.

On the other hand, diesel-powered vehicles present the highest CO emissions of all vehicle types, at approximately 1.27 g/km. Diesel engines are known for producing high CO, especially due to incomplete fuel combustion under certain conditions, such as when the vehicle operates under high load or rapid acceleration. Similar to VOC, all types of EVs have lower pollutants due to CO. BEV and FCEV show low CO due to no combustion with those technologies. However, CO comes from the operational phase of vehicle itself. In addition, FCEV has the lowest VOC and CO among all vehicle types, approximately 0.044 and 0.144 g/km, respectively. FCEVs use hydrogen as fuel, which generates only water as a byproduct.

Figure 6(c)–(f) compares NO_x, PM, and SO_x across various vehicle types. These pollutants show that BEV exhibits the highest of those pollutants. In Figure 6(c), the NO_x level of BEV is primarily due to factors related to electricity sources and energy-intensive production processes. One of the main contributors to NO_x emissions of BEV is power generation that charges the battery during the operation phase, especially when the electricity is sourced from fossil fuel-based power plants, such as coal or natural gas. Coal-fired power plants, which represent the largest energy source in Indonesia, produce significant NO_x emissions during the combustion process. Since BEVs rely entirely on electricity for their operation, an unclean energy source directly influences the NO_x footprint in LCA calculations.

Figure 6(d) and (e) present PM_{2.5} and PM₁₀ across various vehicle technologies. The results for both PM reveal similar

distribution patterns, although their magnitudes differ. PM_{2.5} exhibits lower values than PM₁₀, as PM_{2.5} is a subset of PM₁₀, and its measurements inherently reflect lower quantities than those of PM₁₀. ICEV vehicles show relatively low PM_{2.5} and PM₁₀ emissions, although ICEV-CI is slightly larger than ICEV-SI. These PM originate from fuel combustion. Although comparatively lower, such emissions remain environmentally significant because they are directly released through exhaust gases. ICEV-CI produces higher PM than ICEV-SI, mainly due to higher combustion temperatures and compression ratio, which promote increased soot particles formation.

Hybrid electric vehicles that combine an internal combustion engine with an electric motor show lower PM. Using electric motors in certain conditions, such as at low speeds or when stopped, helps reduce emissions from the engine. However, combustion-related emissions remain present, although at lower levels than ICEV. Slightly different from PHEV, this type of vehicle has a higher PM than HEV. Although these vehicles can operate entirely on electricity for short distances, PM comes from the combustion of fuel when engines are used and during the charging process, where the energy source is still dominated by coal-fired or fossil fuel power plants.

In contrast, BEV exhibits the highest PM among all vehicle types displayed. Although BEV does not generate emissions from fuel combustion, the high PM comes from the battery charging process, which still uses coal-fired plants that increase PM. In addition, the production of lithium-ion batteries is highly energy-intensive and often results in significant PM emissions. The mining and processing raw materials such as lithium, cobalt, and nickel require considerable energy input and produce pollution, including PM. Furthermore, the battery manufacturing process, especially if carried out in a country with less stringent environmental standards, can contribute significantly to PM emissions.

Unlike conventional vehicle types, FCEVs exhibit relatively low PM. The results of this LCA indicate that although EVs (BEV and PHEV) have no or lower exhaust emissions, they can still

produce significant PM, especially from the energy sources used. Meanwhile, vehicles equipped with combustion engines, especially those fueled by diesel, remain major contributor to PM from fossil fuel combustion. The findings demonstrate that reducing PM emissions depends not only on reducing vehicle exhaust emissions but also on the existing energy mix system.

Like the previous trend of NO_x and PM values, the high SO_x values for BEV are primarily related to battery production and the source of electrical used for charging. One of the main contributors to SO_x emissions in BEV is electricity generation, particularly, when the power is supplied by fossil fuel-based plants, such as coal or petroleum. Coal contains sulfur and its combustion releases SO_x into the atmosphere. Since BEV relies heavily on electricity, this energy source is also an essential factor in the SO_x footprint.

In addition, the manufacturing lithium-ion batteries for BEVs involves a highly energy- and material-intensive process. The mining and processing of raw materials such as nickel, cobalt, and lithium can also produce SO_x emissions, particularly when these activities rely on fossil fuel-based energy sources. The purification and processing process of raw materials for batteries, such as nickel refining or sulfur processing in some raw materials, can produce high SO_x emissions. These processing plants often use large amounts of energy and may be located in countries with lower emission standards, which can increase total SO_x emissions.

The results of this LCA indicate that vehicles with newer technologies, such as those using electricity or hydrogen as a power source, tend to produce much lower pollutants compared to conventional vehicles with internal combustion engines. The lower pollutants in electric and fuel cell vehicles suggest significant potential to achieve improved environmental performance, particularly when combined with clean, renewable energy sources.

3.3 Greenhouse Gas (GHG) Emissions

Figure 7 presents GHG emissions from different types of electric vehicles, including CH₄, CO₂, and N₂O. Figure 7(a) illustrates CH₄ across various vehicle types. CH₄ is highly potent GHG emission and can originate from various sources, including fossil fuel combustion and energy production processes. CH₄ from ICEV range from approximately 0.3 to 0.42 g/km. These emissions primarily result from incomplete fuel combustion. Gasoline contains hydrocarbons that can produce CH₄ when an incomplete combustion process occurs. Although ICEV-CI is generally more fuel-efficient, it may produce higher CH₄ due to the differences in combustion characteristic and fuel. In

particular, diesel combustion at high temperatures can produce higher CH₄ emissions than gasoline combustion.

The BEV exhibits CH₄ comparable to those of ICEV-CI, at approximately 0.4 g/km. Although BEV has no tailpipe emissions, CH₄ primarily originate from electricity generation to charge the batteries, especially when electricity is generated by fossil-based power plants, such as coal or natural gas. These fuels produce CH₄ during extraction, processing, and combustion.

Based on Figure 3, the energy mix is dominated by fossil fuels, which account for approximately 85% of the total generation, with coal representing the largest share. In addition to CH₄, CO₂ exhibit a similar profile, with ICEV-CI showing the highest value among vehicle technologies. However, FCEV displays the lowest CO₂, as illustrated in Figure 7(b).

All vehicle technologies produces minor N₂O. However, emission levels vary considerably depending on the technology employed. BEV exhibits the highest N₂O emissions, which is primarily due to Indonesia's reliance on fossil fuel-based power plants, especially coal. ICEV-SI also exhibits relatively high N₂O emissions due to the combustion process in their engines. In contrast, HEV and FCEV demonstrate lower N₂O emissions due to a combination of more efficient energy utilization and advanced combustion technology.

Although BEV and HEV can reduce other GHG emissions and local pollutants, they continue to contribute N₂O emissions primarily through the energy supply chain. These findings underscore the importance of transitioning to cleaner and renewable energy sources to support the adoption of EVs and achieve maximum environmental benefits. Moreover, improving the efficiency of power generation technology and hydrogen energy production is essential for further reducing the carbon footprint and environmental impact. Similar to the previous emissions, this analysis reinforces the importance of clean and efficient energy sources in minimizing life cycle GHG emissions, including N₂O, from EVs.

3.4 Global Warming Potential (GWP)

The GWP was evaluated over two-time horizon: 20 years (GWP-20) and 100 years (GWP-100). GWP quantifies the contribution of GHG emissions to climate change across different stages of a vehicle's life cycle, from production to end-of-life. In general, GWP-20 values are higher than GWP-100. GHG emissions, such as CH₄, have a shorter atmospheric lifespan but have a much stronger warming potential in the short term. GWP-20 therefore captures the significant impact of these gases as their concentration in the atmosphere remains high during this period. Although CO₂ persists longer in the atmosphere

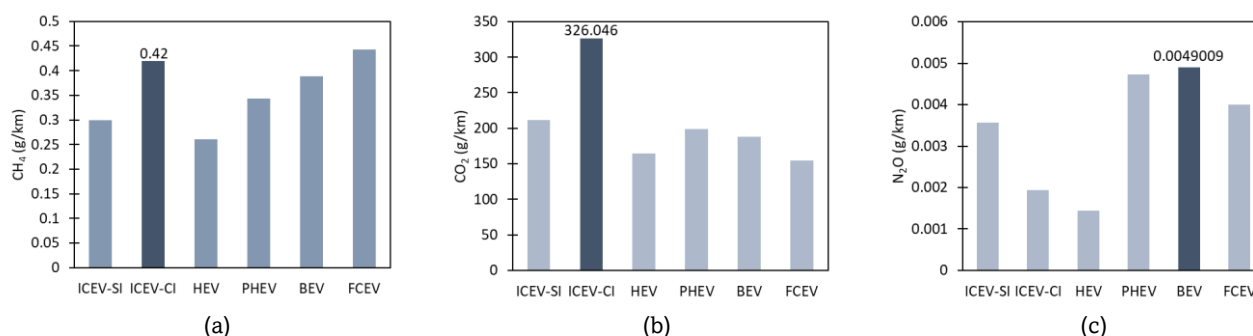


Fig. 7 Profile comparison of greenhouse gas (GHG) emission in g/km for each type of vehicle: (a) Methane; (b) Carbon Dioxide; (c) Dinitrogen Oxides

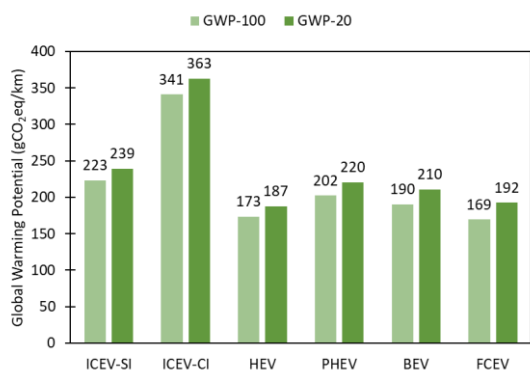


Fig. 8 Comparison of GWP values in gCO₂eq/km for each type of vehicle

compared to other GHG emissions, the warming effects of CO₂ are more pronounced in the first 20 years because it is still in high concentrations after being released.

In contrast, over longer time horizon, some GHG emissions begin to decompose or be absorbed by the oceans, soil, and plants. Consequently, its impact on global warming is decreasing, which is reflected in the lower GWP-100. For 100 years, although gases such as CO₂ continued to contribute to global warming, the decrease in the effectiveness of short-lived gases caused the value of GWP-100 to be lower than that of GWP-20. The magnitude of GWP-20 is higher than that of GWP-100 because the short-term effects of these gases are more intense.

Figure 8 illustrates that ICEV vehicles exhibit relatively high GWP on a 100-year horizon (approximately 300 gCO₂eq/km) and 20-years (higher). ICEV-SI and ICEV-CI produce significant CO₂ emissions from combustion, directly contributing to GWP. ICEV-CI shows the highest GWP among all vehicle types, with very high values at GWP-20 (approximately 380 gCO₂eq/km). HEV exhibits a lower GWP (approximately 150 gCO₂eq/km). Combining electric motors and gasoline engines helps reduce CO₂ emissions during use but energy-intensive battery production processes and not completely clean power sources still contribute to GWP, especially in the short term. FCEV exhibits the lowest GWP. Direct emissions from FCEVs are almost zero, but hydrogen production using natural gas reform or electrolysis has a significant environmental impact. However, the energy-intensive production process makes this impact more visible in the short term.

Battery electric vehicles exhibit interesting results, such as BEV's GHG emissions being higher than HEV's. Although BEV is more environmentally friendly during operation, it continue to face challenges to energy production and batteries manufacturing across the life cycle. In contrast, fossil fuel

vehicles exhibit high GWP due to direct CO₂ emissions from fuel combustion. To reduce overall GWP, it is essential to improve energy efficiency and accelerate the transition to renewable energy sources in vehicle production and operational.

3.5 Sensitivity Analysis of VKT

Figure 9(a) compares the air quality impact of various vehicle technologies across increasing vehicle kilometer traveled (VKT) of up to 25,000 km. The results indicate that, as VKT increases, the air quality impact generally decreases for all vehicle types, although the trends vary in steepness and final values. Among the vehicle types, ICEV-SI and ICEV-CI have the highest air quality impact, remaining consistently above the other options. BEV and FCEV show the lowest impacts, with FCEVs performing the best overall due to their significantly lower emissions. PHEV and HEV occupy a middle position between conventional ICEV and BEV, reflecting their hybrid nature and dependence on both fossil fuels and electric power. These trends emphasize the environmental benefits of transitioning to EVs to reduce emissions and improve air quality over time. In particular, BEV demonstrate significantly reduction in air quality per VKT.

Figure 9(b) illustrates that GWP decreases with increasing VKT for all vehicle technologies, reflecting efficiencies gains or the averaging of emissions over longer operational distances. Among the technologies, ICEV-CI exhibits the highest GWP, followed by ICEV-SI, indicating the significant environmental burden of conventional fuel-based vehicles. In contrast, FCEV exhibits the lowest GWP, underscoring its potential to minimize GHG emissions. BEV also performs significantly better than ICEV, demonstrating the benefits of electrification. HEV and PHEV achieve intermediate reductions, positioning them as transitional technologies but still less effective in reducing GWP than fully electric or hydrogen-powered vehicles. These findings emphasize the critical role of zero-emission technologies like BEV and FCEV in mitigating climate change while highlighting the importance to phase out ICEV to achieve meaningful reductions in transportation-related GHG emissions. Furthermore, this technologies underscores the potential of EV to improve air quality and climate performance by minimizing air pollution and GHG emissions.

However, the clear gap between ICEVs and EVs reinforces the importance of transitioning away from fossil fuel-based transportation. Hybrid technologies like HEV and PHEV demonstrate moderate benefits, acting as transitional solutions, but do not achieve the environmental performance of fully electric or hydrogen-powered vehicles. The benefit of BEV would be clear when the energy mix uses greener power plants, such as wind, solar, and hydro. This analysis strongly supports

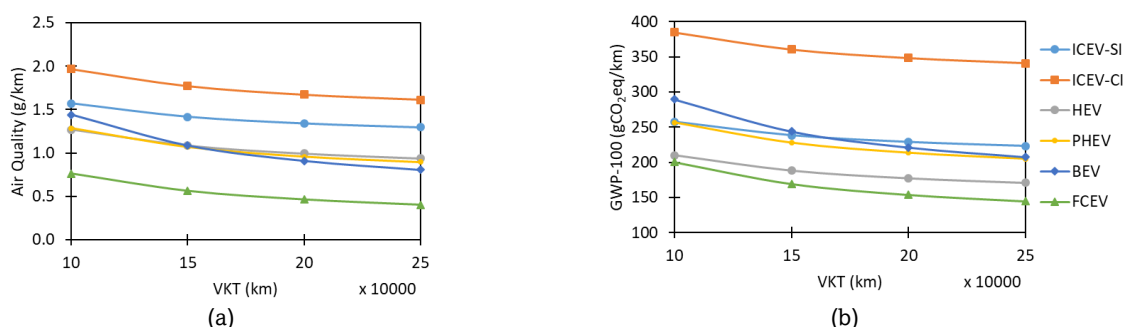


Fig. 9 Sensitivity analysis: (a) air quality; and (b) GWP-100 against vehicle kilometer travelled (km)

policies and consumer choices that prioritize BEV and FCEV as a key enablers of sustainable and low-emission mobility.

Although EVs have significant benefits, battery becomes a further problem due to waste and other mining and extraction of battery material. Vehicle and battery recycling become significant concerns to minimize the negative impact on the end-of-life phase. Figure 10 compares the GWP-100 across various vehicle types, both with and without recycling benefits considered. The inclusion of recycling benefits leads to a reduction in GWP across all vehicle types. The incorporation of recycling benefits significantly improves the GWP performance of vehicles. For example, BEV demonstrates a 16.8% reduction in GWP due to recycling, reflecting the environmental value of material recovery in the vehicle and battery life cycle. When compared to findings from other studies, the environmental benefits of recycling BEV demonstrate a reduction in GWP values, which exhibit regional and national variation. This variation arises primarily from differences in the electricity grid mix across countries. Kallitsis *et al.* (2022) investigated the recycling benefit in three different countries. The study examined how geographic specificity influences combined battery production and recycling, revealing it as a major factor in the variability of GWP impacts. In China, Kallitsis *et al.* (2022) found the reduction of GWP (kgCO₂eq/kWh) up to 35%, while in North America reach 30%. In Europe, they found a reduction of up to 27.5%. However, Kallitsis *et al.* (2022) have not included the recycling of vehicles.

Despite these improvements, ICEVs remain the least sustainable option, even with recycling benefits. This analysis highlights the importance of transitioning to cleaner vehicle technologies and implementing effective recycling practices to further reduce life cycle emissions. Among the available alternatives, BEV remains the most promising technology for reducing transportation-related GHG emissions while maximizing recycling benefits.

The increasing adoption of EVs has led to a growing demand for critical raw materials such as lithium, cobalt, and nickel, thereby necessitating the development of efficient waste management systems for their recovery. In the future, the waste management of batteries (such as lithium-ion) will become essential rather than optional, driven by several key factors: 1) Higher expenses and inconsistent availability of essential raw materials required for lithium-ion battery production, 2) safety issues related to the accumulation or disposal of used lithium-ion batteries, 3) environmental issues with the disposal of used lithium-ion batteries (Sommerville *et al.*, 2021). Similarly, Beaudet *et al.* (2020) identified economic and environmental drivers such as to alleviate toxicity, safety, and contaminations

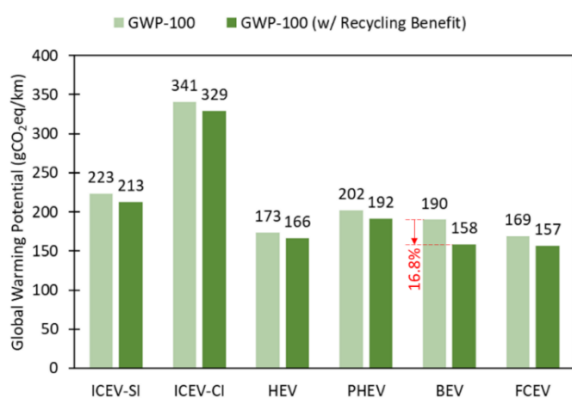


Fig. 10 Comparison GWP-100 with recycling benefit

risks, to reduce the carbon footprint, cost, reliance on mineral extraction, reliance on specific suppliers, and to generate local economic activity. Moreover, waste management lithium-ion batteries could ensure a stable supply of raw materials for EV batteries, while minimizing energy consumption and environmental emissions throughout the battery life cycle (Rajaeifar *et al.*, 2020). Consequently, the recycling of battery materials is crucial for future sustainability.

End-of-life EV batteries can be managed through three primary pathways, depending on their design, quality, and state of health (SOH): remanufacturing, repurposing, and recycling (Chen *et al.*, 2019). Remanufacturing involves restoring EV batteries to their original functionality for continued use in automotive applications. Repurposing represents an alternative approach for managing end-of-life batteries, whereby batteries are reconfigured for "second-life" applications, such as stationary energy storage. This process enables additional value creation by extending battery service life beyond initial automotive use. Recycling constitutes the third pathway and is essential for accommodating battery packs regardless of their design or state of health. Although remanufacturing is the most preferred end-of-life option for batteries, it requires the highest standards of battery quality. In contrast, recycling is often regarded as less favorable due to the significant material and energy losses involved in the process (DeRousseau *et al.*, 2017).

Key strategies in waste battery management include material recovery, second-life applications, eco-design, and regulatory frameworks with supporting incentives, as illustrated in Figure 11. Material recovery in battery recycling refers to the process of extracting valuable materials from used or end-of-life batteries so they can be reused in the production of new batteries or other products. This process typically involves recovering critical elements such as lithium, cobalt, nickel, manganese, and copper, which are commonly found in EVs and other lithium-ion batteries. Advanced recycling technologies focus on extracting valuable metals and other components from end-of-life batteries. Hydrometallurgical and pyrometallurgical processes are commonly employed to recover battery materials (Liu *et al.*, 2019). In particular, the pyrometallurgical recovery processes demonstrate significant potential for enhancing environmental benefits, especially in supporting net-zero emission targets within the energy system (Liu *et al.*, 2024).

Before recycling, EV batteries can often be repurposed for less demanding second-life applications, such as energy storage systems (Colarullo and Thakur, 2022). Extending the operational lifespan of batteries reduces waste and delays the need for material recovery. Moreover, designing batteries with recyclability in mind through eco-design principles represents a proactive approach for improving recycling efficiency. Modular designs and more accessible materials to disassemble and process can streamline recycling operations (Thompson *et al.*, 2020).

Without any supportive policies, the implementation would be nothing. Therefore, regulatory frameworks and incentives play an important role to implement end-of-life process for batteries. Governments and policymakers play a crucial role in encouraging battery recycling by implementing regulations and providing financial incentives (Shao *et al.*, 2018). Mandating manufacturer responsibility and establishing recycling targets can drive innovation and investment in this sector. Several countries have implemented a recycling battery policy. The US considered policy to not include LIBs as hazardous material and banned landfill disposal for LIB waste, while Japan has required manufacturers to be responsible for setting up efficient and

sustainable recycling systems (Zhang *et al.*, 2021). Some countries applied reward-penalty mechanism (Tang *et al.*, 2019).

3.6 Policy Implications

The air quality improvements observed during periods of reduced mobility, as reported by Progiou *et al.* (2022), suggest that transportation policies can play a transformative role in achieving environmental targets. Transitioning to EVs and redesigning transport systems under cradle-to-cradle principles offer a more durable solution to the air pollution challenges observed during temporary lockdowns.

Building on recent evidence, key policy implications emerge to support a sustainable transition to EV within the broader context. Governments play a pivotal role in shaping regulatory frameworks, financial incentives, and enabling infrastructure to ensure that EV adoption not only reduces emissions but also enhances resource efficiency and fosters green economic development (Li *et al.*, 2022, Mekky and Collins, 2024).

A fundamental policy priority lies in promoting eco-design principles within vehicle manufacturing. Designing vehicles that are easier to disassemble, recycle, and repurpose can significantly reduce material waste and improve life cycle efficiency (Mayyas *et al.*, 2019). Public policy can facilitate this transition through fiscal incentives, such as tax credits or subsidies for manufacturers that incorporate recycled materials, modular components, or biodegradable parts into their designs. Moreover, mandatory regulatory standards for recyclability and material efficiency can further encourage the adoption of sustainable design practices across the automotive industry. By embedding sustainability at the design phase, environmental considerations become an integral component of product development rather than an afterthought (He *et al.*, 2021).

In tandem, integrating circular economy principles into national transportation and industrial strategies represents a systemic policy approach (Yildizbasi *et al.*, 2024). National policies can establish minimum targets for recycled content in vehicle production, require LCA for infrastructure and mobility-related projects, and promote industrial symbiosis—whereby waste or by-products from one sector are utilized as inputs in another. Such policies enable alignment between climate action and industrial development, facilitating more efficient resource use and cross-sectoral innovation.

Energy policy must also be aligned with the decarbonization of the EV ecosystem. Although EVs produce no tailpipe emissions, their overall environmental impact depends largely on the energy sources used for charging and manufacturing. Policymakers should therefore support the deployment of renewable-powered EV charging networks and incentivize the use of clean energy in manufacturing processes. Furthermore, policies that encourage vehicle-to-grid (V2G) integration and smart grid compatibility can enhance the resilience and sustainability of national energy systems (Yang *et al.*, 2024).

At the end-of-life stage, the development of robust battery recycling infrastructure is essential for closing the loop on critical material flows. EV batteries contain valuable and finite resources such as lithium, cobalt, and nickel, often sourced from environmentally sensitive regions. Strengthening national recycling capabilities can reduce dependence on primary extraction and mitigate associated environmental impacts. To this end, public policy should support investment in advanced recycling technologies, establish clear guidelines for collection and processing, and implement regulatory instruments such as Extended Producer Responsibility (EPR). These mechanisms hold manufacturers accountable for the entire life cycle of their



Fig. 11 Key strategies in waste battery management

products, as demonstrated in China (Li and Fujikawa, 2023) and the European Union (Nitsch, 2022).

Beaudet *et al.* (2020) identified three strategic policy priorities for catalyzing investment in battery recycling systems: (i) allocating public funding to support research and development (R&D) of innovative recycling technologies; (ii) providing financial support for pilot-scale projects to demonstrate the technical and economic feasibility of recycling processes; and (iii) implementing market-pull mechanisms that create favorable regulatory and economic conditions for lithium-ion battery (LIB) collection and processing.

Finally, none of these policy measures can succeed in isolation. Cross-sector collaboration between government, industry, and academia is crucial for fostering innovation in sustainable mobility and materials management (Maldonado Guzmán and Pinzón Castro, 2023). Such collaborative efforts are essential for overcoming technical and policy barriers, scaling up solutions, and accelerating the commercialization of clean technologies. To maximize the environmental benefits of EV deployment, policy frameworks should address uncertainties related to climate change, resource availability, and infrastructure resilience. Analogous to water management under variable climate scenarios, as discussed by Nydrioni *et al.* (2024), EV policy should incorporate scenario-based planning to anticipate environmental trade-offs and promote long-term sustainability.

By adopting a holistic and integrated policy approach, governments can ensure that the transition to EV not only advances decarbonization goals but also enhances resource security, supports industrial competitiveness, and contributes meaningfully to broader sustainable development objectives.

3.6. Limitation

This study relies primarily on secondary data from publicly available databases and existing literature, which may not fully reflect real-time technological developments or region-specific practices in manufacturing, recycling, and energy sourcing. In particular, assumptions related to material recovery rates, battery degradation profiles, and recycling process efficiencies can introduce considerable uncertainty into the life-cycle analysis. These limitations can result in oversimplified representations of environmental impacts and may obscure critical variability in system performance.

Moreover, the static nature of the life cycle modeling employed in this study constitutes an additional limitation. Static models fail to account for the dynamic changes that occur

over time, including technological innovations, evolving policy landscapes, and the progressive decarbonization of electricity grids. These temporal dynamics play a crucial role in shaping the long-term environmental performance of EVs and related technologies.

4. Conclusion

4.1 Concluding Remarks

Adopting a cradle-to-cradle approach within the LCA framework is essential for advancing sustainable transportation. This approach facilitates the transition toward minimizing environmental impacts, promoting sustainable production and energy consumption systems, and supporting a circular economy. By evaluating the environmental impacts of various vehicle technologies, this study highlights the potential to reduce energy consumption, harmful pollutants, and GHG emissions. The findings indicate that, although EVs offer significant reductions in operational emissions, challenges remain in material extraction and end-of-life management, particularly for battery components. EVs (HEV, PHEV, BEV, and FCEV) exhibit significantly lower total energy consumption than ICEV. Consequently, transitioning to HEV, PHEV, BEV, and FCEV can markedly reduce fossil fuel consumption, with BEVs demonstrating the greatest potential for integration with renewable energy sources. Furthermore, EVs generate considerably lower levels of air pollutants and GHG emissions than ICEVs. Nevertheless, further efforts to increase renewable energy utilization across all vehicle technologies are critical for achieving sustainable energy consumption.

Although BEVs are more environmentally friendly during operation, they continue to face challenges related to energy production and battery life-cycle impacts. Fossil fuel vehicles exhibit high GWP due to CO₂ emissions from fuel combustion. To reduce overall GWP, it is essential to improve energy efficiency, increase the use of renewable energy in vehicle production and operations, and enhance vehicle material recycling.

To achieve sustainable transportation goals, this study recommends several strategies, including developing robust recycling infrastructure, designing vehicles with sustainability principles in mind, and implementing policies that incentivize environmentally friendly practices across the transportation sector. These measures reduce environmental impacts while fostering innovation and resilience in addressing global challenges such as climate change. By integrating cradle-to-cradle principles into vehicle technology development and policymaking, the transportation sector can make substantial progress toward a greener and more sustainable future.

4.2 Future Works

Future works should prioritize improving data quality and model realism by incorporating primary data from key stakeholders across the EV value chain. Collaborations with battery producers, recycling facilities, and vehicle manufacturers can provide more detailed, accurate, and context-specific information on material flows, degradation profiles, and recovery efficiencies. Additionally, advancing life cycle modeling through the integration of dynamic variables is essential. Future studies are encouraged to adopt dynamic life cycle assessment (d-LCA) approaches that reflect temporal changes such as technological advancements in battery chemistry, improvements in energy infrastructure, and policy evolution related to recycling and carbon regulation. These

improvements will enable more nuanced evaluations of long-term sustainability impacts, thereby supporting policymakers and industry stakeholders in making more informed decisions toward the transition to circular and low-carbon mobility systems. However, advancing sustainable vehicle technologies requires not only innovations in design and recycling but also alignment with integrated climate governance systems. The framework proposed by Martín-Ortega *et al.* (2024) illustrates how transparent and systemic approaches can enhance accountability and policy coherence in emissions reduction across sectors, including transportation.

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