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Environmental life cycle assessment of conventional and electric vehicles: lessons learned from selected countries

Muhammad Idris [1,*], Raldi H. Koestoer [2]

[1] School of Environmental Science, University of Indonesia; muhammad.idris21@ui.ac.id
[2] School of Environmental Science, University of Indonesia; ralkoest@gmail.com
* Correspondence: muhammad.idris21@ui.ac.id

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Abstract
Electric vehicle (EV) is an alternative expected to be tail-pipe emission-free and improve public health. Switching conventional or internal combustion engine vehicles (ICEVs) to EVs becomes a potential strategy for realizing urban sustainability. The study aims to review the environmental impact between ICEV and EV in Lithuania, China, Canada, Poland, Czech Republic, Italy, United States, and Australia. Then, the review result is compared to the Indonesia context as lessons learned. A comparative study with a qualitative descriptive method was carried out. The main activities are a literature review. The works of literature were collected, classified, and reviewed to find out significant findings on the environmental impact of ICEV and EV. Assessing the vehicle in all life-cycle (LC) phases is an essential issue. The entire LC of products may significantly impact the environment due to the utilization of raw materials through a process that causes adverse environmental impacts. Therefore, Life-cycle assessment (LCA) is proposed to estimate the environmental effects related to all the LC stages of EVs. Thus, LCA could be a critical tool. Numerous cases in several countries show that EVs were not always more environmentally friendly than ICEVs. The review indicates that EVs and electricity-generating mix scenarios play a significant role in performing LCA due to the performance of an EV is extremely dependent on the energy consumed through its operation phase. Additionally, the results show how significant renewable energy sources (RES) are in the electricity-generating mix that provides different environmental impacts. In the Indonesia context, the environmental impact of EV is predicted to be higher than ICEV due to the electricity generating mix is still lower than 20% in 2023. Optimizing the electricity generating mix scenario by increasing the RES, implementing clean technology power plants, and applying vehicle recycling are excellent strategies to promote sustainable development in the EV industry. However, economic and social aspects shall be considered to get comprehensive results in further research.
Keywords: conventional vehicle; electric vehicle; environmental impact ; life cycle assessment

1. Introduction

Currently, the world faces environmental sustainability, energy security, and climate change challenges (García-Olivares et al., 2018). Energy and transportation sectors with fossil fuels contribute 70% of global greenhouse gas (GHG) emissions (Duan et al., 2016). Transportation accounts for 25% of CO_2 emissions generated by fossil fuel combustion (IEA, 2021; Leach *et al.*, 2020). Today, around 95% of global transportation is powered by liquid fuels from fossil fuel-based (Leach et al., 2020).

The current global trend of eco-friendly energy has grown since the Paris Agreement that imposed every country responsible for climate change due to the global average temperature increase (Li et al., 2016; Van Soest et al., 2021). The authorities have therefore invested in setting GHG emissions levels to decrease air pollution, especially in the transportation sector. Countries and regions worldwide are aggressively encouraging the electrification of the transportation sector by substituting internal combustion engine vehicles (ICEVs) or conventional vehicles. New technology like electric vehicles (EVs) contributes significantly to reduce fossil fuel-based utilization, which impacts the decline in GHG emissions (Aziz et al., 2016; Shaukat et al., 2018).

As a participant in the automotive industry, EV technology is a desirable alternative believed to be emission-free and enhance public health. The worldwide EV market has taken an enormous breakthrough in the past decade. More than 10 million EVs were on the world's roads in 2020 and still growing. China has become the global leader in the EV industry (Du et al., 2017). Substituting ICEVs for EVs appears to be a potential step toward achieving urban sustainability. The electrification of transportation plays a strategic role in the emergence of sustainable systems. Therefore, the utilization of EVs is encouraged massively by governmental policies (Bañol Arias *et al.*, 2020; Meisel & Merfeld, 2018; Thorne & Hughes, 2019; Wang *et al.*, 2019).

Recently, the term sustainability has become an important paradigm in the utilization of products (Hagen *et al*., 2020; Watkins *et al*., 2021). The entire life-cycle (LC) of products may significantly impact the environment due to the utilization of raw materials through a process that causes adverse environmental impacts (Tang *et al.*, 2021; Ternel *et al.*, 2021; Verma *et al.*, 2022; Wu *et al.*, 2018). The significance of the environmental impacts has increased to involve environmental aspects in their product development (Ahmad *et al.*, 2018). Thus, this requires an assessment of the environmental aspect of the product during its entire LC. Although EVs considerably contribute to reducing emissions, it is important to investigate their environmental impact. Life-cycle assessment (LCA) is proposed to estimate the environmental effects related to all the LC stages of EVs. LCA investigates the environmental impact throughout its LC, from the extraction of raw material and processing to production (cradle), distribution, utilization, recycling, and final disposal (grave) (Ilgin & Gupta, 2010).

Apart from the development of conventional vehicle technology (Veza *et al.*, 2020), research and development of EV technology are currently being carried out on a large scale, including in Indonesia (Setiawan, 2019; Subekti, 2022; Utami *et al.*, 2020). Therefore, this has the potential for vehicle disruption from conventional technology to electric. As stated in the Nationally Defined Contribution (NDC) document, which has been enhanced in 2022, Indonesia has promised to reduce 31.89% and 43% of its GHG emissions using a business as usual (BAU) and conditional scenario, respectively. The government proposes several strategic actions to achieve this target: adopting EVs and additional renewable energy in the power generation mix.

Indonesia plans to increase EV adoption by decreasing CO_2 emissions from vehicle exhaust. GHG emissions from the transportation sector in 2016 reached 134.5 Mt or 318% greater than in 1990. The transportation sector contributed 24.71% of GHG emissions, making it the second largest emitter after energy sector emissions (Veza *et al.*, 2022). In line with the Indonesian Government's commitment to reduce GHG emissions and considering the contribution of the transportation sector to GHG emissions is quite large, the Indonesian government created a program called the Battery-Based Electric Vehicle Program.

Regardless of the promising EV technology, finding an academic paper addressing the environmental impact or LCA of EV compared to ICEV in Indonesia is challenging. Other countries have dominated recent articles, especially the United States, China and Europe region. The previous studies of LCA discuss specific aspects of the product (Ahmadi, 2019; Wu *et al.*, 2018; Zheng & Peng, 2021). To the best author's knowledge, none of them reviews LCA of the vehicle and compares it to the Indonesia context with the specific issue in the characteristic of the energy system. Therefore, this study aims to review the environmental impact between ICEV and EV from numerous investigations and bring the result to the Indonesia context as lessons learned and the preliminary study to get a brief profile of the impact. The review was based on LCA in different countries/regions. However, the significance of LCA provides a scientifically rigorous and comprehensive approach to assess and communicate the environmental impacts of products, processes, or systems (Finkbeiner *et al.*, 1998). It enables informed decision-making, supports sustainability analysis, and contributes to the development of policies and practices that promote sustainable development, especially sustainable transportation systems (Dong *et al.*, 2018).

2. Methods

This study reviews the application of LCA for ICEV and EV in selected countries to explain whether EVs are more ecologically aware than ICEV and their environmental impact. In the field of environmental sustainability, a previous study, such as by Verma *et al.* (2022) and Marmiroli *et al.* (2018), reviewed the LCA of EV and ICEV using a similar approach but different stressing point. This study builds upon the work by introducing several basic concepts of EV and LCA. This provides a more comprehensive understanding of the product's LC. Then, it expands to the Indonesia context as the objective of this study. It is important to understand the technology and how the technology should be incorporated into LCA. A comparative study with a qualitative descriptive was performed through the following three steps. The steps described the main activities of the research to investigate the environmental impact of ICEV and EV. The literature study is the main activity.

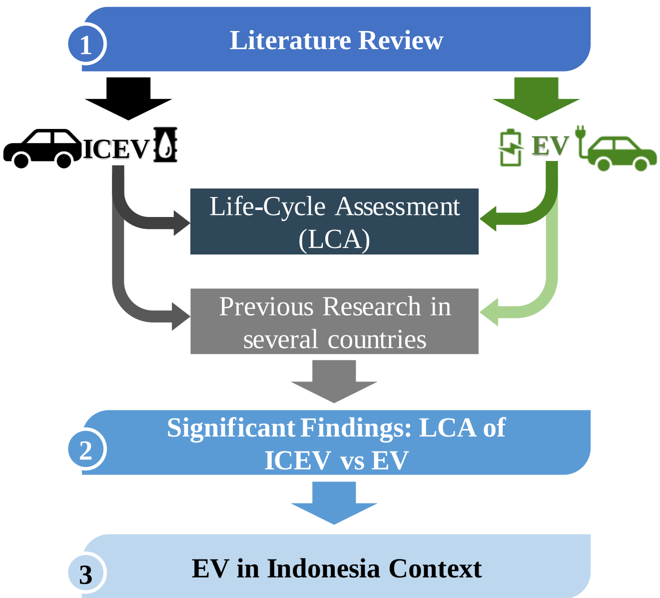

Figure 2.1 Activities of review for the environmental impact of vehicle

The step-by-step activities are followed and organized in the section of this paper, as shown in Figure 2.1. In step 1, a literature review from various papers was conducted by collecting papers with keywords such as "environmental impact" and "life-cycle assessment" in vehicles (ICEV and EV). Types of vehicles were identified by explaining the technology of electric vehicles.

Then, LCA literature was collected, classified, and reviewed. Initially, LCA methodology was discussed briefly for the primary introduction of works. Step 2 is to provide significant findings on the environmental impact of ICEV and EV from various references in different countries (Lithuania, China, Canada, Poland, Czech Republic, Italy, United States, and Australia). Finally, step 3 provides the significant findings by bringing them to the Indonesian context with the current status of EV development.

Life cycle assessment (LCA) is a recognized technique to calculate the potential environmental impacts of the process, activity, or product all through the life cycle (LC) (Curran, 2013). Identifying environmental factors along its entire LC is a sophisticated and complex process. Thus, a systematic analytical tool for the environmental assessment of a vehicle's LC is required. Some products are dominated by environmental impacts during production (Bianco *et al.*, 2021), utilization (Athanasopoulou *et al.*, 2018; Challa *et al.*, 2022; Kawamoto *et al.*, 2019) and disposal stages (disposal) (Shafique & Luo, 2022). LCA is intended to quantify and investigate the flow of materials and energy used in each phase of a product's life, together with the accompanying emissions and waste that will be discharged into the surrounding environment. In all phases, it is impossible for a vehicle to be developed, produced and marketed without accompanying design, raw material extraction, manufacture, transportation/distribution, utilization, disposal, recycling and energy resources. However, these phases are often neglected in environmental impact assessments.

3. Results and Discussion

3.1. Various Electric Vehicles

Regarding energy sources or prime movers, vehicles can be categorized into ICEVs and EVs. Most of the ICEVs applications are petrol and diesel engines which have been widely used since the early 19^{th} century. Based on the method to get energy for a powertrain, EVs can be categorized into the full battery (BEV), hybrid (HEV), and plug-in hybrid (PHEV) (Dižo *et al.*, 2021; Lavee & Parsha, 2021; Nour *et al.*, 2020). The other type of EV comes from the utilization of hydrogen, which is called fuel-cell (FCEV) (Andrzej *et al.*, 2021). Combining FCEV with BEV creates a fuel-cell hybrid (FCHEV) (Das *et al.*, 2017). Figure 3.1 describes all the typical classifications of vehicles. However, EV in this study will refer to BEV to clarify and focus.

BEVs have no fuel tank. Therefore, BEVs are also called "pure EVs". A BEV only uses one type of electric powertrain device. Energy is saved in batteries. This vehicle requires to be charged at charging stations using an electric plug-in with a special socket. BEVs do not produce any GHG emissions or noise pollution. As a result, it benefits the environment.

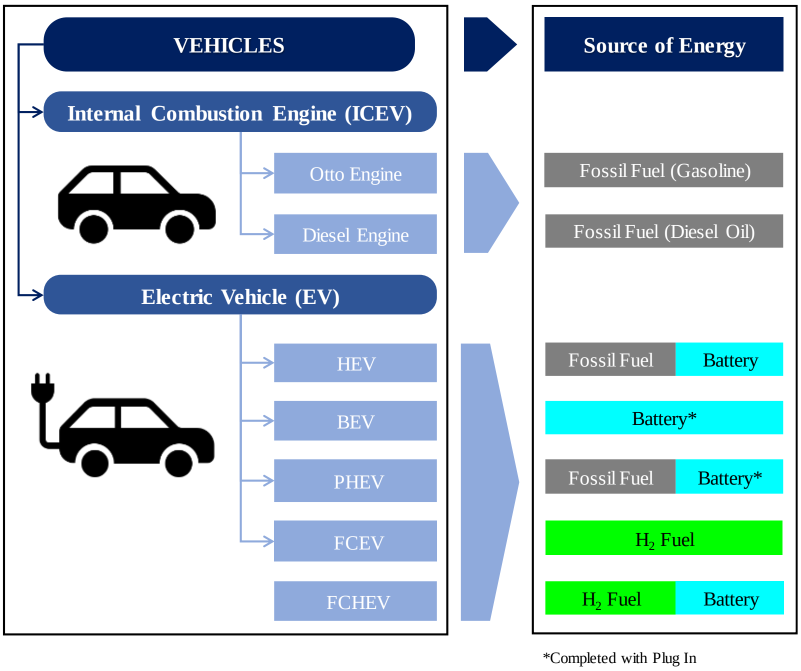

Figure 3.1 The difference in vehicle classification

An HEV uses an internal combustion engine (ICE) and a motor to operate the vehicle in a fuel-efficient mode. The motor acts as a backup powertrain in certain operational conditions and does not require charging at a charging station, except PHEV. Similar to HEV, a PHEV uses an ICE and an electric powertrain. Yet, it can be charged at a charging station. The battery capacity is usually greater than an HEV (Dižo *et al.*, 2021). While running on battery power, PHEVs emit no tail-pipe emissions; however, they emit emissions when generating electricity at a power plant. The PHEV is primarily powered by electricity and is only used for short distances. Longer trips require gasoline, which is only necessary when depleted battery power. While PHEVs have a more extended range than BEVs, they have several disadvantages, including a higher initial cost than BEVs; and not being environmentally friendly because they emit emissions at the generation end. To address these issues, numerous studies have been focusing on analyzing ways to improve the battery performance (i.e., charging time, cooling system analysis, testing and ranging) and optimize the package (weight and size) (Verma *et al.*, 2021).

Another type is fuel cell electric vehicles (FCEV or FCV). FCEVs have attracted great attention due to their zero-emission operation. FCEVs, like BEVs, are powered by an electric motor, but they use a fuel cell instead of a battery. FCEVs transport hydrogen in tanks of special design. The electricity generated by the fuel cells is routed to an electric motor that powers the vehicle. The vehicle is fueled by hydrogen, and the fuel cell converts the chemical energy contained in the hydrogen gas to electric energy to power the electric motor. Hydrogen can be produced through the combustion of fossil fuels such as natural gas or through water electrolysis.

Fuel cell hybrid electric vehicle (FCHEV) is the other configuration of EV as a combination of FCEV. Sometimes, FCHEV is categorized as HEV, which adopts a fuel-cell stack as the main power combined with an energy storage system to power the electric motor (Fathabadi, 2018; Pukrushpan *et al.*, 2004). There is no ICE in this configuration.

3.2. Advantages of Electric Vehicles

Electric vehicles have shown promising prospects by reducing tail-pipe emissions compared to ICEVs throughout their life cycle, which also contributes to public health (Abas *et al.*, 2019; Pipitone *et al.*, 2021). Emissions will be concentrated and localized in the power generation area because EVs are very dependent on the energy mix that exists in the area's electricity system (Choi *et al.*, 2018). In addition to reducing emissions, EVs also contribute to reduce noise pollution in urban areas. EVs are significantly quieter than ICEVs (Nour *et al.*, 2020), different from ICEVs with high noise due to explosions in the combustion process. Transport on highway traffic is the most common source of noise (Steinbach & Altinsoy, 2019; Thompson & D Ixon, 2018).

Electric vehicles have easier construction than ICEVs because of their compact construction, fewer moving parts, and simple transmission, especially for pure EVs (Nour *et al.*, 2020). An electric vehicle has lower construction complexity than ICEV multi-speed transmission. However, EVs are more complicated with electric controls. Moreover, EVs have higher reliability than ICEVs due to worn moving parts due to vibration, engine explosion or fuel corrosion (Sanguesa *et al.*, 2021). Due to the fast response of electric motors, EVs are very responsive, have good acceleration and have high torque (Kawamura *et al.*, 2011).

Electric vehicles require little maintenance while minimizing maintenance costs compared to ICEVs. EVs have a simple electric motor-battery system, and the current generation of lithium-ion battery packs is smaller than their predecessors (Rozman, 2019). The mechanical components of EVs require less maintenance. Maintenance costs for EVs are assumed to be 30% lower than ICEVs (Bakker, 2010; Delucchi & Lipman, 2001).

3.3. Life Cycle Assessment Methodology

The LCA of ICEV and EV is conducted following the standard specified in ISO 14044. The LCA is executed in four steps. The basic framework of LCA is shown in Figure 3.2. In the first step, the objective of LCA is specified, such as the background and application. The scope is defined, particularly the definition of functional units, system boundaries, impact categories, and data requirements. In this step, assumptions are also specified and justified.

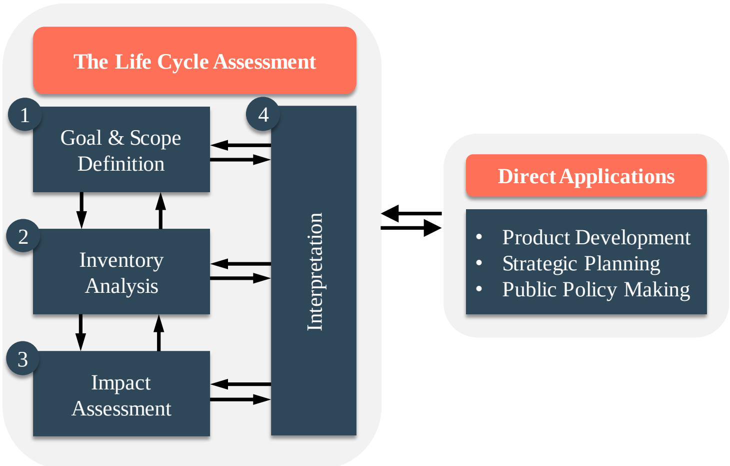

Figure 3.2 Basic framework of LCA based on ISO 14040, 2016

The inventory analysis step includes the energy and material flow within the boundary and their interaction with the environment, which is described by input and output. In the impact assessment step, inventory analysis results are associated with impact categories, such as acidification, climate change, eutrophication, ecotoxicity, ionizing radiation, human toxicity, ozone depletion, respiratory inorganics, land use, photochemical ozone formation, and resource depletion. An impact assessment is then performed, usually covering three areas of protection: human health, the natural environment, and resource (Wolf *et al.*, 2012). Lastly, in the interpretation step, outcomes from LCA are interpreted according to the goal and scope. This step comprises sensitivity, completeness, and consistency checks (Serenella *et al.*, 2015).

Commercially software packages of LCA are available to assist LC inventory and impact assessment. Several LCA software packages include GREET, GaBi, Umberto, SimaPro, and OpenLCA. The selection of LCA software is crucial. Each has unique characteristics that might vary regarding database availability, functionality, data quality management, user interface, and modeling principles (Silva *et al.*, 2017). The LCA outcomes depend on databases, methods, and impact assessment models developed by software to assist the LCA process (Lopes Silva *et al.*, 2019).

Numerous researchers have proposed an analysis of the well-to-wheel (WTW) process for comparing the emission contribution of various vehicle technologies (Athanasopoulou *et al.*, 2018; Que *et al.*, 2015). Another terminology refers to cradle-to-grave (CTG), which is generally applied also for LCA (Ferg *et al.*, 2019; He *et al.*, 2020; Song *et al.*, 2018; Tagliaferri *et al.*, 2016). Figure 3.3 depicts the comparison of WTW analysis for ICEV and EV.

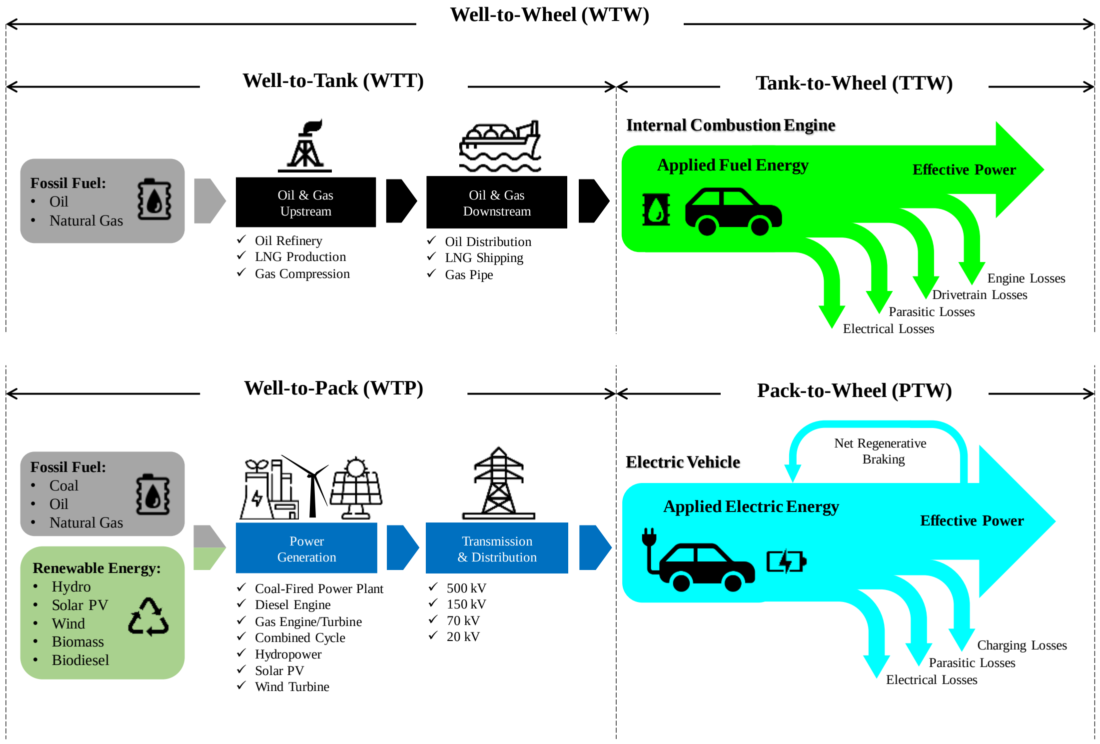

Figure 3.3 Scenario The comparison of WTW analysis for ICEV and EV
(Source: adapted from Athanasopoulou *et al.* (2018))

WTW analysis has been commonly applied to understand energy consumption in the vehicle systematically. WTW analysis brings up the entire energy flow, from the exploration/extraction of fossil fuels in upstream business (well) or electricity generation to the operation of a vehicle (rotating of the wheel). Energy consumption is a fundamental analysis of energy efficiency. The upstream-to-downstream process should be investigated to determine the overall energy efficiency to describe the efficiency of vehicles.

However, drawbacks were found in LCA, particularly about subjectivity by the individual who carries out the assessment. Decision-making in LCA is often influenced by the preferences of the individual or organization conducting the analysis. This can lead to different interpretations of the data and make the analysis results less objective. Furthermore, simplifying boundaries is perceived as a limitation and makes it different for each person carrying out the assessment. Even though the ISO standard provides a definition and a general framework for assessment, the result has multi interpretations (Curran, 2014).

Besides, the LCA framework does not consider the economic and social aspects. Other techniques shall be applied to gather information about a product's economic and social impacts. This is sometimes perceived as a limitation in LCA (Curran, 2014). However, although LCA has some limitations, it remains a valuable tool to help organizations and individuals understand the environmental impact of their products or processes and identify areas where improvements can be made.

3.4. Lessons Learned from Selected Countries

Nowadays, power generation and transportation run dominantly with fossil fuels which contribute 70% of global GHG emissions (Duan *et al.*, 2016), whereas the transport sector accounts for 25% of CO_2 emissions generated by fossil fuel combustion (Leach *et al.*, 2020). More than 90% of global transportation is powered by fossil fuel-based, such as diesel oil, gasoline, or petrol (Leach *et al.*, 2020).

Despite EVs having better perception than ICEVs, it is crucial to thoroughly investigate them by not only considering in utilization phase (tail-pipe emission) but also the entire LC of vehicles. To fully compare ICEVs with EVs, researchers must account for impacts associated with fossil fuel production, electricity generation mix, vehicles, batteries production, vehicle use, and disposal phases in the LCA of EVs. Numerous comparative LCA of ICEV against EV and review articles on the areas have been published in the last decade. Two main impact categories were identified: climate change in $kgCO_2eq$ and human toxicity in kg 1.4 DBeq. However, other impact categories were discussed in numerous studies.

Petrauskienė *et al.* (2020) compared the LCA of ICEV and EV in Lithuania. ICEVs were performed based on diesel and petrol fuel. Meanwhile, EV was assessed under different electricity generation mix scenarios forecasted for 2015-2050. The results reveal that EV in 2015 had a higher GHG emissions impact of 26% and 47% than ICEV-petrol and ICEV-diesel, respectively. Even though renewable energy sources (RES) in 2015 were more than 53%, EV still has a higher climate change impact category than ICEV. EV with electricity generation mix in 2050 has 54% lower impact than EV with more than 92%of RES in electricity generation mix in 2015.

Unlike Petrauskienė *et al.* (2020), Qiao, Zhao, Liu, He, *et al.* (2019) compared ICEV-gasoline and EV in China. They investigated the GHG emissions of the Cradle-to-Gate (CTG), Well-to-Wheel (WTW), and Grave-to-Cradle (GTC) phases. CGT, WTW, and GTC represent the manufacturing, utilization, and recycling phase. The result shows that the LC GHG emissions of EV in 2015 was 18% lower than ICEV. This value decreased in 2020 due to the reduction of emission factor of electricity generation mix. Even though the electricity generation mix was dominated by fossil fuel-based, with 68% generated from coal-fired power plants, EV had a lower environmental impact than ICEV. It was indicated that the power plant applied clean power technology and a recycling process for EV.

Burchart-Korol *et al.* (2018) evaluated the environmental impact of vehicles in Poland and Czech Republic. They compared ICEV-petrol and EV. They investigated the GHG emissions of the Cradle-to-Gate (CTG). EV was analyzed under different electricity generation mix scenarios forecasted for 2015-2050. It considered scenarios of smart grids for charging EV batteries that could be supplied exclusively from RES. The result shows that the LC GHG emissions of EV in 2015 was 3% and 25% lower than ICEV for Poland and Czech Republic, respectively. The value decreased in 2050 for both countries due to the increase of RES. EVs combined with RES offer the potential to reduce the negative impacts on the environment.

In Italia, Pero *et al.* (2018) presented a comparative LCA of ICEV and EV. ICEV was performed based on gasoline fuel. The analysis of LCA follows a cradle-to-grave approach.

The results reveal that EV had a lower impact by 37% than ICEV. Similar to Pero *et al.* (2018), two years before, Tagliaferri *et al.* (2016) also assessed the LCA of ICEV and EV in Italia with a similar approach. The result shows that EV had a lower impact by 25% than ICEV-diesel. However, the ICEV-diesel by Tagliaferri *et al.* (2016), fueled by soybean biodiesel, was lower than ICEV-gasoline by Pero *et al.* (2018)

In another continent, Onat *et al.* (2015) investigated the WTW approach for various vehicles in United States. They compared BEV, PHEV, and HEV by considering specific regional driving patterns, electricity generation mixes, and vehicle and battery manufacturing impacts. The result showed that based on the average electricity generation mix scenario, BEVs were the smallest carbon-intensive vehicle option, while HEVs were the most energy-efficient option. Based on the marginal electricity generating mix scenario, adopting BEVs was found to be an unwise policy given the existing and near-future marginal electricity generation mix. On the other hand, BEVs could be superior to other alternatives if the required energy to generate 1 kWh of electricity is below 1.25 kWh.

Bicer & Dincer (2018) analyzed the LCA of three types of vehicles in Canada: ICEV, HEV, and BEV. ICEVs were fuelled by gasoline, hydrogen, diesel, ammonia liquefied petroleum gas (LPG), methanol, and compressed natural gas (CNG). Meanwhile, EVs were HEV using 50% gasoline - 50% electricity and BEV using 100% electricity. The results show that BEV with a renewable mix had the lowest environmental impact on global warming impact. However, BEV with electricity generation mix had three times higher than BEV with RES. ICEV-hydrogen yields the most environmentally benign option among other vehicles due to lower fuel consumption and higher energy density.

Sharma *et al.* (2013) evaluated LCA for three different vehicles in Australia. They investigated the LC CO_2 emissions of ICEV-gasoline, ICEV-diesel, and EV. They considered lifetime driving distance and CO_2 emissions from battery production. The results presented that CO_2 emission from EVs was greater than ICEV from the additional CO_2 emissions from battery production. However, in regions where RES and clean technology power plants are widely applied, EVs' total LC CO_2 emissions become lower than ICEV. A summary of lessons learned from selected countries is depicted in Figure 3.4.

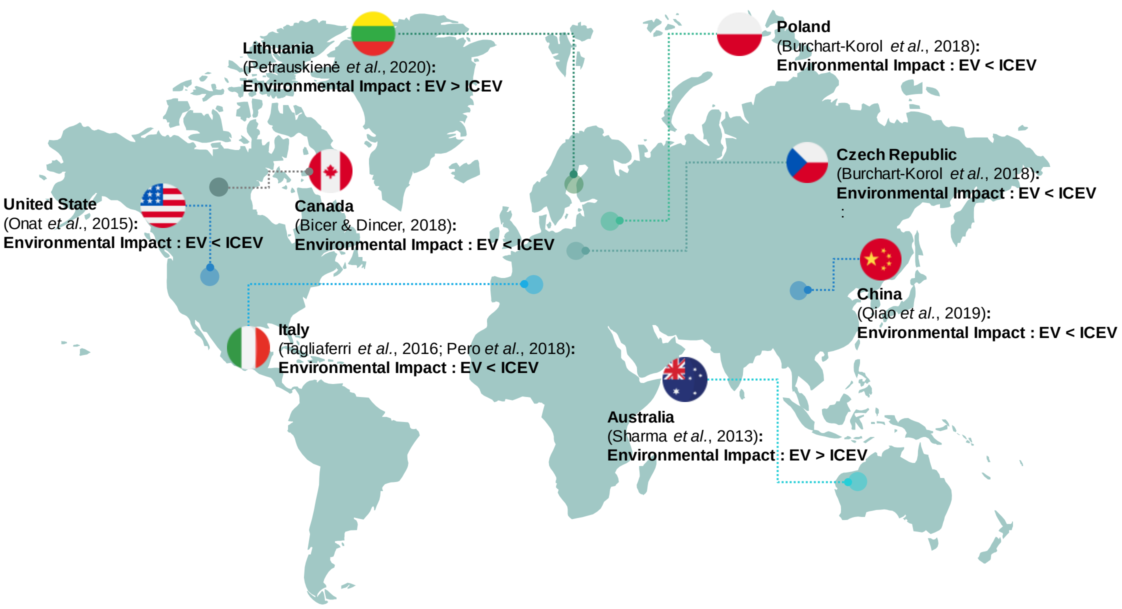

Figure 3.4 Summary lessons learned from selected countries

Based on the above reviews, it is concluded that the main contributing factor to the environmental impact of EVs is the source of electricity used to charge the batteries.

Increasing renewable energy, decreasing fossil-fuel-based, and enhancing clean power technology for electricity in EV utilization can further decrease the total environmental impacts. Enhancement of clean power technology can decrease GHG emissions in the WTW phase.

In addition, although EVs do not discharge emissions directly during utilization, batteries' production, disposal, and recycling processes take a significant environmental impact. The energy consumption and resource throughout the material extraction, manufacturing, and utilization of the battery are not as low-carbon as expected. Therefore, battery carbon emissions must be fully considered when promoting EVs. Battery recycling can reduce the GHG emissions of the CTG phase.

3.5. Indonesia Context: Current Status, Opportunities, and Challenges

Indonesia has a population of 275.75 million in 2021 and is projected to reach 278-364 million by 2060 (Roser *et al.*, 2023). The population was directly correlated with energy consumption, particularly CO_2 emissions contribution. In 2019, the transport sector contributed annual CO_2 emissions of more than 149 Mt, which is 80% larger than one decade ago in 2009. The transport sector contributed up to 10% of CO_2 emissions, making it the third highest CO_2 emitter below the land-use change and electricity sector (Ritchie, 2020).

As stated in the enhanced Nationally Determined Contribution (NDC) document in 2022, Indonesia has pledged to reduce 31.89% and 43% of GHG emissions by using business-as-usual and conditional scenarios, respectively. The Government proposed to achieve this target by adopting several mitigation actions. The adoption of EVs and additional renewable energy in the electricity-generating mix are several strategies for achieving the ultimate goal.

Several policies have been issued to accelerate EV adoption. Through Presidential Regulation No. 22/2017 about the National Energy General Plan, the Government targeted 2025 to adopt 2.1 million and 2,200 units of 2-wheeled and 4-wheeled EVs, respectively. In 2019, the Government issued Presidential Regulation No. 55/2019 concerning the Acceleration of the Battery Electric Vehicle Program for Road Transportation. Data from the Ministry of Transportation in 2021 revealed that Indonesia had 14.400 registered EVs; 1,656 registered for 4-wheeled, 262 for 3-wheeled, and 12,464 for 2-wheeled EVs.

As one of the major automotive markets in Asia, Indonesia has a significant role in the development of vehicles. The market size is still growing consistently, even though the pandemic hit in 2020. Indonesian transport was dominated by motorcycles. The massive number of motorcycles indicates that the recent Indonesian public transport cannot provide the mobilization needs (Veza *et al.*, 2022). In this condition, Indonesia has an enormous potential to electrify the current transportation system, particularly ICEV.

Besides, to accelerate EVs, the Government provided incentives for domestic production. However, EV technology is relatively new for the domestic automotive industry and requires development stages to achieve full readiness in society, with several bottlenecks, such as commercialization, safety, and integration parameters (Maghfiroh *et al.*, 2021). Utami Utami *et al.* (2020) analyzed a non-behavioral EV adoption intention model by considering the sociodemographic, financial, technological, and macro-level. The high opportunity to adopt EVs (motorcycles) in Indonesia reach 82.90%. However, the realization requires infrastructure readiness and costs.

This study focused on the Jawa-Bali region as a representative of Indonesia. This region was selected because more than 60% of the vehicle population is in Jawa-Bali. In addition, in terms of the electricity system, the Java-Bali region contributes 72% of the electricity system in Indonesia. As discussed in the previous section, electricity sources play a significant role in performing EVs. The performance of an EV is highly dependent on the electricity consumed during its operation phase. Nowadays, the electricity generation mix is still dominated by coal, 76% of which is generated by coal-fired power plants. The electricity generation mix from RES is still around 10%.

Figure 3.5 shows the scenario electricity generation mix 2021–2030, which implies the growth of renewable energy is still lower than 18%. This challenging condition makes the comparison of EV in Indonesia is predicted to have a higher impact than ICEV. Due to dominant fossil fuel utilization, GHG emissions are a key consideration in determining the strategy of EV adoption.

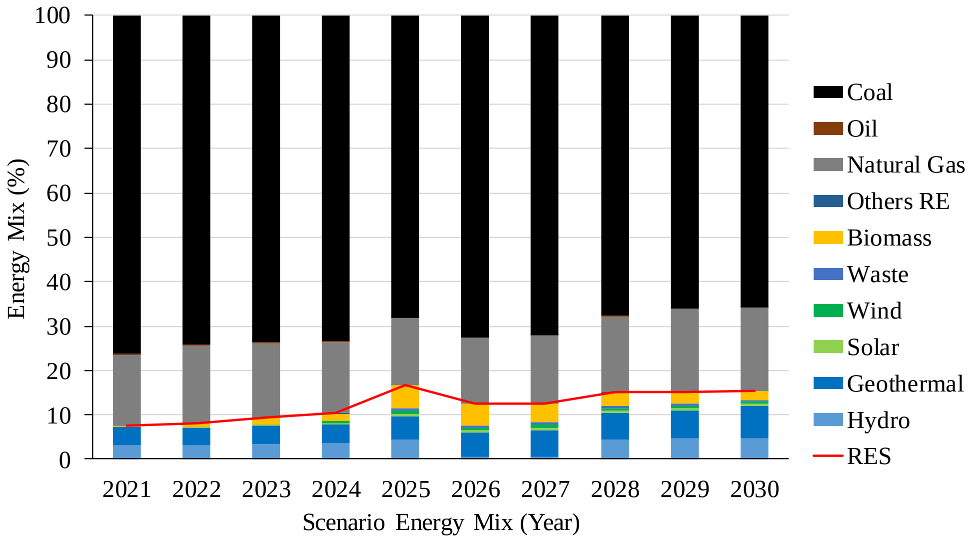

Figure 3.5 Scenario electricity generation mix 2021-2030 in Indonesia (Jawa-Bali Region) (Source: RUPTL (2021))

Figure 3.6 shows the detail of the electricity generation mix for renewable energy only. In 2025, renewable energy will increase drastically due to the termination of coal-fired power plants. However, the renewable energy mix during this projection is still low. The emission factor for the electricity system is 0.848 t CO_2/MWh in 2021. It is projected to be 0.736 t CO_2/MWh in 2030 due to the positive contributions from the utilization of natural gas, RES, and environmentally friendly technologies in coal-fired power plants, such as ultra-supercritical (USC), $DeNO_x$, $DeSO_x$, and carbon capture technology. Compared to other countries/regions, EVs showed significantly lower CO_2 emissions than ICEV in most European countries, with an emission factor of 0.300 tCO_2/MWh (Capros *et al.*, 2016). However, other cases show that a higher emission factor produces lower LC CO_2 emissions (Kawamoto *et al.*, 2019). It indicates that LC CO_2 emissions depend not only on emission factors in the electricity generating mix but also on other parameters, such as lifetime driving distance, estimation of battery production emission, and LC approach.

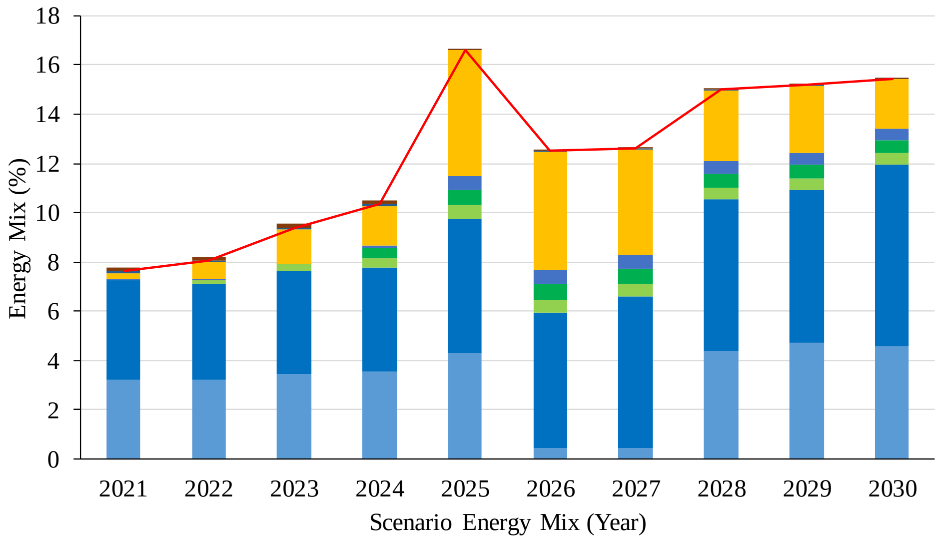

Figure 3.6 Scenario renewable energy mix 2021-2030 in Indonesia (Jawa-Bali Region)
(Source: RUPTL (2021))

To the best knowledge of the authors, no study compares the LCA of ICEV and EV in Indonesia. Therefore, it is important further to investigate the LCA of Indonesian vehicles in detail, to get the actual profile. Moreover, the result can assist in taking strategic policies to adopt EVs in Indonesia with specific programs.

Taking everything into account to accommodate the adverse environmental impact, Indonesia has significant challenges in the economic and social aspects of EV adoption. Therefore, it is important to carry out a comprehensive study, not only related to environmental but also related to economic and social impacts. The program, such as enhancement in the electricity generating mix to fully renewable energy, implementation of clean power technology, and EV battery recycling, are significant challenges due to contributing significantly to the cost of EV and the cost of electricity production that must be borne by EV consumers. Qiao, Zhao, Liu, & Hao (2019) investigated the environmental and economic advantages of EV recycling, especially for the battery. As a result of recycling an EV, the environmental advantages per technology cost are approximately 241.3 MJ and 36.3 kgCO_2eq and the net income is approximately 473.9 dollars, and the net savings are approximately 25.6 GJ and 4.1 tCO_2eq. Other research regarding battery LC has been investigated by other researchers (Ferg *et al.*, 2019; Raugei & Winfield, 2019; Yang *et al.*, 2018). Even though the investigation results have different profiles, the contribution of battery recycling was significant in environmental impact.

However, EV technology is still developing amidst various emerging issues, such as safety and risk (Muzir *et al.*, 2022). As an electric system, it should be a good notice to evaluate electricity's risks and safety issues. As a tropical country with a rainy season, Indonesia has not yet been free from the flood in several cities. Therefore, the system must be fully protected from flood cases. Moreover, explosion risks are also potential. Many cases were occurred in worldwide due to short circuits, electric shocks or car crashes.

Nowadays, charging infrastructures are still the main issue in Indonesia. The lack of availability of charging infrastructure along the driving way is an important issue for users. Therefore, for long-distance driving, the use of EV is still difficult to be realized. Charging infrastructures are concentrated around big cities, such as Jakarta.

4. Conclusions and Recommendations

EVs play a significant role in stimulating a sustainable transportation system and are expected to decrease tail-pipe emissions. In addition, the electricity generation mix provides a different impact from the EV, which is very dependent on the electricity consumed by EV during its operation phase. Most studies underlined the reduction of LC emissions when the electricity generation mix produces relatively low emissions, such as renewable or clean energy. There is no specific approach for one region. However, the methodology can be applied to another region with different characteristics of electricity generation mixes and vehicle types. Although LCA has limitations, LCA can figure out the environmental impact comprehensively and comparably. The percentage of RES in the electricity generation mix is the most influential in decreasing the environmental impact of EVs. This review concludes that countries/regions with a high percentage of fossil energy have considerable challenges in getting advantages from EVs according to LC emissions. This insight provides a preliminary result to describe how significant the environmental impact of EVs is in Indonesia, especially in Jawa-Bali region. Short and long-term planning shall be carried out to accommodate EV adoption. The potential benefits of implementing EVs are widely open, especially regarding the increasing the renewable energy percentage, improved technology of the batteries, and the sustainability of battery's material by recycling approach.

This qualitative descriptive research has not yet performed the specific LCA of EV and ICEV in Indonesia. However, to know the real figure of LCA in Indonesia, it requires specific data on product and life cycle inventory. Hence, the result of the investigation could be a quantitative basis for policy and decision-making. In addition, potential research should be performed, not only from the environmental aspect but also from economic and social points of view, which would be advanced to achieve a sustainable transportation system.

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Author Contribution

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