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Assessment of CO2 Emission of Electric Vehicles based on Life Cycle Assessment and System Dynamics Methodology

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Abstract: The promotion of electric vehicles (EV) adoption has emerged as a prevalent policy approach in numerous countries for reducing CO2 emission. Given the significant contribution of road transportation to CO2 emissions, the replacement of fossil fuel-based conventional vehicles with EV represents a viable strategy to mitigate emissions. However, the successful implementation of EV necessitates a comprehensive assessment throughout its entire life cycle. The use of EVs may reduce CO2 emission from the vehicles, however the increasing consumption of eletric power during its use may potentially potentially lead to higher CO2 emissions from the electric power generation, in particular in countries wherein fossil-based energy soures yet dominate the electric mix such as Indonesia. This study aims to conduct an assessment of CO2 emission of EV adoption in comparison to that of internal combustion engine vehicle (ICE) throughout their life cyles in Indonesia. Simultaneously, a system dynamics model is developed to depict the adoption process of EV and ICE based on Bass diffusion model. The system dynamics model is also used to simulate the impact of government policies in promoting the use of EVs.

Keywords: *electric vehicles; internal combustion engine vehicles; life cycle assessment; system dynamics; bass diffusion model.*

1 Introduction

The global stock of electric vehicles (EVs) has experienced exponential growth in recent years [1]. By 2021, the number of electric vehicles reached 16.5 million units. This growth is primarily driven by the increasing sales of EVs in China, continental Europe, and the United States which have emerged as dominant players in the global electric vehicle market. Figure 1 exhibits the remarkable growth in the adoption of electric vehicles worldwide, highlighting several countries that have experienced substantial increases in the number of EVs.

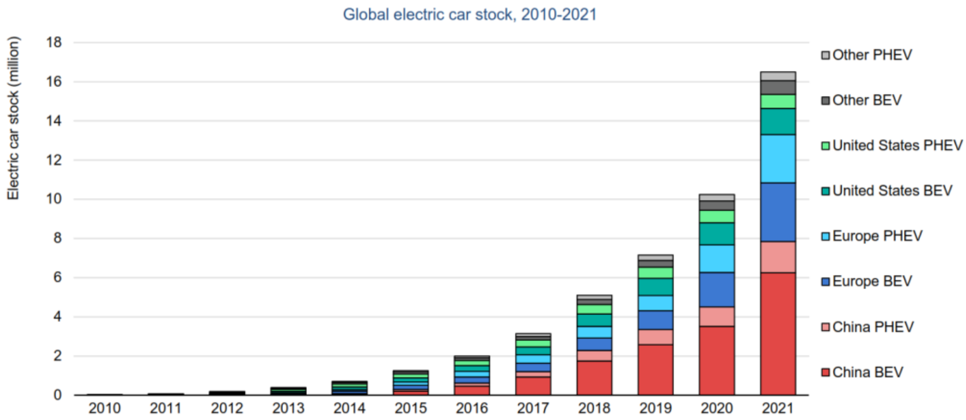

Figure 1 The global development of electric vehicles [1]

The promotion of electric vehicles and their widespread adoption is a key strategy employed by numerous countries to achieve zero emissions. By transitioning to EVs as a primary mode of road transportation, the aim is to reduce reliance on fossil fuels and subsequently decrease CO2 emissions. The increasing adoption of EVs as a means of vehicle electrification is foreseen to bring about signifiant impacts on several economic sectors, in particular the automotive industry and its supporting sectors, the electric energy sector, and also on the environmental conditions. Electrification of road transportation is expected to shape the future of transportation, enhance environmental sustainability, and induce transformation of the energy landscape [2].

The increased adoption of EVs in several countries can be attributed primarily to the supportive policies implemented by their respective governments. These policies aim to incentivize and promote the usage of electric vehicles, making them a more economically viable and competitive option compared to internal combustion engine vehicles (ICEVs). By offering financial incentives, such as tax credits, subsidies, and rebates, governments effectively reduce the initial purchase price of EVs, making them more affordable for consumers. The use of EVs is expected to reduce CO2 emissions from road transportation sector by 70-85% because electric vehicles do not emit any direct emissions [3]. According to the International Energy Agency [4], the transportation sector is the third-largest contributor to CO2 emissions, following the electricity and industrial sectors. The use of EVs is considered one of the solutions for reducing emissions [3]. Research by Shuai Pan et al. [5] supports the notion that widespread EV usage will have a positive impact on the environment and health. It is projected that by 2050, the global use of EVs will reduce the consumption of fossil fuels by 50% and lower CO2 emissions by 75%.

The goal of achieving zero emissions cannot be solely accomplished by a significant increase in EV adoption. It requires government support in form of comprehensive policies [6]. In Indonesia, the support for EV is continuously being enhanced through the implementation of PP no. 55 of 2019, which focuses on accelerating the Battery Electric Vehicle program for road transportation [7]. This initiative aims to improve infrastructure support and provide incentives to boost the EV business sector in Indonesia. However, the electrification of vehicles may encounter several challenges, including (1) battery degradation, (2) high investment costs, and (3) social barriers [8]. The use of EV in Indonesia faces several challenges, primarily high costs, particularly in electric vehicle batteries. There are three main contributing factors hindering its progress: (1) the absence of a standardized vehicle policy; (2) inadequate power plant infrastructure; and (3) less attractive investment opportunities outside Java.

The aspects needed for the EV ecosystem include charging infrastructure, models and supply of electric vehicles, public awareness and acceptance, supply chains for batteries and electric vehicle components, as well as incentives and supporting policies from the government [9]. In Indonesia, these aspects have started to be developed, although they are yet relatively limited.

The utilization of EV holds the potential to significantly decrease CO2 emissions within the transportation sector. However, the effectiveness of this emission reduction is subject to limitations, particularly in countries heavily reliant on high-carbon electricity sources [3]. The full impact of carbon emissions reduction in the context of vehicle usage extends beyond the immediate perspective of end-users. It is essential to consider the overall implications of EV throughout the entire value chain. In the case of Indonesia, where the energy grid has a high carbon emissions profile, the electrification of vehicles may not effectively lead to a substantial reduction in total emissions. The primary energy mix of power plants in Indonesia in 2021 was dominated by coal (66.01%), followed by gas (17.16%) and hydropower (6.90%). In Indonesia, power plants utilizing new renewable energy sources account for only 0.19% of the overall energy mix.

In addition, the growth of EV adoption will directly contribute to an increased demand for electricity consumption, potentially resulting in increased CO2 emission in particular from energy sector for producing electricity, and from battery industry for producing lithium-ion batteries which demand high energy, and from recycling process of the batteries. Accordingly, it is important to conduct a comprehensive assessment of the environmental impact of EV across its entire life cycle, rather than solely focusing on specific phases. By considering the entire life cycle of EV, including raw material extraction, battery production, vehicle manufacturing, electricity generation, vehicle operation, and end-of-life management, we can gain a more accurate understanding of their environmental implications. This holistic assessment approach enables us to identify potential areas for improvement and implement strategies to minimize emissions and maximize the overall environmental benefits of electric vehicles.

Several previous studies have focused on specific phases of EV's life cycle. Research by Vilchez and Jochem [10] estimated the emissions produced from the production and usage phases of EV which took into account the emission resuted by production process of electric energy. The study results indicated that emissions of EV at the *Well-to-Tank* phase and manufacturers using coal as an energy source, CO2 emissions would increase as EV becomes more prevalent. In addition, study by Kannagara et. al [11] indicated that CO2 emissions during the usage phase of EV were lower compared to ICEVs. However, in scenarios with high emission intensity, EV could potentially have higher overall CO2 emissions. Overall, these studies emphasize the importance of considering the entire life cycle of EV and taking into account factors such as energy sources and manufacturing processes to accurately assess the environmental impact of EV.

The production of EVs and their components, particularly batteries, has been found to generate higher CO2 emissions compared to ICEVs. Particularly, the battery system in electric vehicles accounts for 50% of the CO2 emissions produced during the overall production process [12]. In contrast, previous research conducted by Franzò & Nasca [13] suggests that the adoption of EVs can actually reduce total CO2 emissions when compared to ICEVs. One noteworthy discrepancy between the studies conducted by Franzò & Nasca and Hirz & Nguyen is the omission of CO2 emissions attributed to the production of electric vehicle (EV) batteries that significantly contributes to CO2 emissions in the adoption of EVs. Considering the energy requirements associated with EVs, it becomes crucial for the power generation sector to account for the environmental impacts throughout the entire life cycle of EVs. The scope of this study encompasses the production phase of EVs, the EV battery industry, the usage of EVs, the End-of-Life phase of EVs, and electricity production, taking into consideration the energy mix as guided by government policies. By examining these aspects collectively, a more comprehensive understanding of the environmental implications of EVs can be obtained, facilitating the identification of potential areas for improvement and the formulation of effective strategies to mitigate emissions throughout the entire life cycle of EVs.

Based on previous research conducted by Xia [13], it is evident that the assessment of CO2 emissions throughout the life cycle of EVs and ICEVs reveals significant variations. Multiple studies have indicated that the adoption of EVs alone does not automatically guarantee a reduction in CO2 emissions. The impact of EVs on emissions is heavily dependent on the energy grid composition of each respective country. Therefore, considering the power generation sub-system within the analysis of the EV adoption system is crucial for accurately assessing the overall impact of CO2 emissions. By incorporating the electric power generation sector, a comprehensive evaluation of the environmental implications of EVs can be conducted, highlighting the intricate relationship between vehicle electrification and CO2 emissions at a broader system level.

2 Research Method

This study consists of two parts. The first part is a life cysle assessment (LCA) of EV to calculate the CO2 emission of a single unit of EV throughout its life cycle, in comparison to that of an ICEV. The life cycle assessment is performed using the OpenLCA software, utilizing the comprehensive dataset available in the Ecoinvent database. The Ecoinvent database has been widely used in numerous life cycle assessment studies and provides the necessary dataset for this particular research.

The second part is a system dynamics modeling to simulate the adoption progress of EV and ICEV within a time horizon. The system dynamics simulation uses the output of LCA to calculate the CO2 emission of EVs and ICEVs as the their adoptions evolce within the respective time horizon. To facilitate the simulation of the system dynamic model, Powersim Studio 10 software is utilized.

Life Cycle Assessment (LCA)

According to Hisan Farjana et al. [14], LCA is a comprehensive and quantitative analysis of the environmental or social impacts caused by products, processes, or systems throughout their entire life cycle. This analysis incorporates life cycle thinking, which considers the consequences on the environment, economy, and society associated with a product. The LCA method is described in ISO 14040:2006 and ISO 14044:2006 (ISO Standards Policy and Strategy Committee, 2006), which provide principles and frameworks for assessing the impact of a product's life cycle. The LCA study comprises four phases: goal and scope definition phase, inventory analysis phase, impact assessment phase, and interpretation phase. The LCA method calculates the impact of a product on various factors studied throughout its life cycle.

The Goal and Scope Definition phase is the first step in the LCA method. It involves determining the objectives and scope of the study, establishing the boundaries, and defining the goals to be achieved through evaluating a product. This phase encompasses the following aspects [15]:

- Objective: Clearly defining the purpose and goals of the LCA study.
- Scope: Identifying the boundaries and extent of the study, including the life cycle phases to be considered.

- Functional units: Establishing the functional units for comparing different products or systems.
- System limits: Defining the boundaries of the system being analyzed, such as the specific processes or components included.
- Data quality: Ensuring the reliability and quality of data used in the assessment.
- Critical Review Process: Outlining the process for obtaining feedback and reviewing the study methodology and results.

Following the completion of the Goal and Scope Definition stage, the next step is the Life Cycle Inventory (LCI) Analysis. This stage involves implementing the initial plan established during the goal and scope definition and follows the analysis steps outlined in ISO 14044:2006 [16].

The Life Cycle Impact Assessment (LCIA) utilizes the information gathered during the LCI phase to identify and assess the potential impacts of the analyzed processes or systems [17]. ISO 14040/14044 outlines the stages of LCIA as follows:

1. Selection of impact categories, indicators, and model characteristics: In this stage, the relevant impact categories and indicators are chosen based on the objectives and scope of the study. Additionally, model characteristics are defined to quantify and assess the impacts.
2. Classification: The selected database is utilized to classify the inventory data according to the chosen impact categories. This process involves allocating the inventory flows to the specific impact categories.
3. Characterization: The characterized impact outcomes are determined based on the classified inventory data. This step involves assessing and quantifying the impacts associated with each inventory flow within the chosen impact categories.

During the LCIA stage, the impact assessment is conducted by linking the data from the LCI results to the impact categories being analyzed. The category endpoint is determined as the final result of the system where the analyzed impact occurs.

System Dynamics

System Dynamics refers to the application of a mindset that focuses on controlling dynamic behavior within a managed system [18]. In this approach, the control of managed systems, which involve interconnected components, is achieved by influencing the components that can be controlled. The system being analyzed exhibits feedback relationships and dynamic behavior.

The System Dynamics methodology is applied to model the relevant system representing the adoption process of EVs and ICEVs. The System Dynamics model describes the structure among the system components, specifying the types of variables, relationships between variables, and model parameters. The relationships between system variables are elucidated using mathematical relationships and basic functions, including delay, smoothing, and table functions. Prior to creating the simulation model structure, the relevant system is described and conceptual model is defined described using causal loop diagram (CLD) to provide a clear understanding of the system being studied.

3 Research Explained

Part 1: LCA of EV and ICEV

Goals and Scopes

In LCA, the scope refers to a defined set of boundaries that distinguish the components of the system under study from those outside of it. It is crucial to clearly define the scope and provide a clear explanation of the level of accuracy and precision of the system review. Determining the scope is an iterative process that can be refined and developed further with additional data. The extent and level of accuracy of the system boundaries depend on the specific objectives of the research being conducted [19].

The objective of this study is to calculate the CO2 emissions generated throughout the entire life cycle (cradle-to-grave) of an EV and an ICEV. The research scope is based on the determined system boundaries. The study encompasses the following system boundaries: Input of raw materials for the production of EVs and ICEV; Four main processes within the EV and ICEV supply chain, i.e., production, transportation, use phase, and end-of-life. Figure 2 exhibits the system boundary and provides a visual representation of the four main processes involved in the life cycle of both EV and ICEV.

Life Cycle Phases

Production Phase

The production phase of both EV and ICEV involves two main components: glider and powertrain, and Lithium-ion Battery for EV. The glider refers to vehicle frame, while the powertrain acts as the driving force for vehicle. In the case of EV, the Lithium-ion Battery serves as the main energy source. EV production can take place domestically or abroad, whereas most of the production of ICEV occurs in Indonesia.

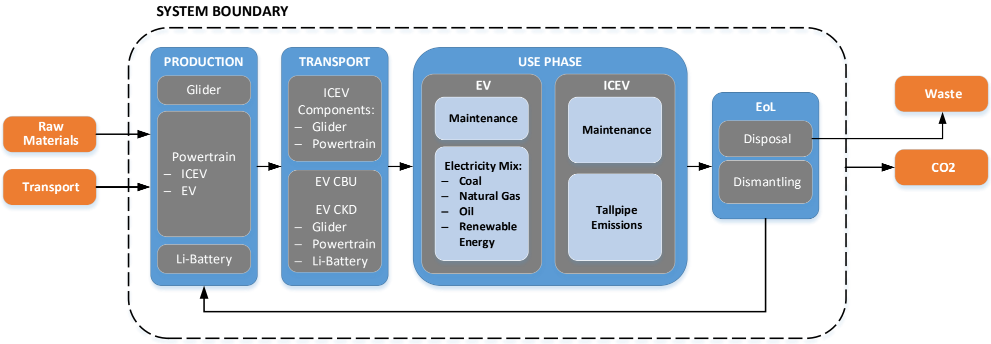

Figure 2 System Boundary

Transport Phase

The transport phase involves the transfer of vehicles from production facilities to wholesalers. Two modes of transportation are used: sea transport via container ships and land transport via trucks. Sea transport is specifically utilized for imported electric vehicles.

Use Phase

During the use phase, vehicles produce direct CO2 emissions in the case of ICEV, while EV increases the demand for electrical energy as its primary power source. The emissions generated from EV in this phase include the impact of the electricity generation at power plants. Additionally, maintenance processes are carried out during this phase.

End-of-Life Phase

The end-of-life phase involves the disposal and dismantling of vehicles. Vehicle dismantling allows for the recovery and reuse of several components. This recycling process contributes to the sustainability of the production cycle.

LCI Inventory Model

The collection of relevant data is based on previous studies that have been conducted and by utilizing datasets from the Ecoinvent Database. The Ecoinvent modules used in this study is summarized in Table 1. The table provides an overview of the specific Ecoinvent modules utilized, including their respective references and version information. The collected data from these modules are crucial for conducting a comprehensive analysis in this study.

Table 1 Process and Ecoinvent Module.

Process	Ecoinvent module (in OpenLCA)	units
1. Production Phase		
a. Production of EV Powertrains	market for powertrains, for electric passenger cars	kg
b. Production of EV Glider	market for gliders, passenger cars	kg
c. Production of EV Batteries	market for battery, Li-ion, LiMn2O4, rechargeable, prismatic	kg
d. EV Assembly	passenger car production, electric	number-of-item
2. Transport Phase		
a. Transport for EV Powertrains	transport, freight, sea, container ship transport, freight, lorry 16-32 metric tons, EURO6	kg*km
b. Transport for EV Glider	transport, freight, lorry 16-32 metric tons, EURO6	kg*km
c. Transport for EV Batteries	transport, freight, sea, container ship	kg*km
d. Transport EVs	transport, freight, lorry 16-32 metric tons, EURO6	kg*km
3. Use Phase		
a. Use PhaseEV	transport, passenger car, electric	km
4. End-of-Life Phase		
a. EoL EV	market for manual dismantling of used electric passenger cars	items

The data for the EV and ICEV life cycles in the Ecoinvent database is derived from research conducted by Habermacher [20]. In Indonesian market, based on data provided by Gaikindo, the Hyundai Kona EV and Hyundai Ioniq EV were the best-selling EVs in 2021. For the purpose of this study, the Hyundai Ioniq EV is selected as the reference vehicle for conducting the life cycle assessment (LCA). Detailed specifications of the Hyundai Ioniq EV can be found in the table provided below.

Table 2 EV Specification [21]

Model	Vehicle Mass(Kg)	Max Power(Kw)	Battery Capacity (Kwh)	Battery Technology
Hyundai Ioniq Ev 2019	1575	100	38.3	NMC 622

The 2019 Hyundai Ioniq EV has a consumption value of 0.138 kWh/km and a driving range of 311 km, according to the Worldwide Harmonized Light Vehicles Test Procedure. It is assumed that the vehicle will cover a mileage of 150,000 km during its lifetime, which is a commonly used value in previous studies. According to data from Gaikindo, South Korea is the dominant exporter of EVs to Indonesia, accounting for 58% of the total imports. Other countries such as Japan, Germany, and the UK also export EVs to Indonesia.

Regarding the electricity mixes considered in this study, the following table presents the data based on the Ministry of Energy and Mineral Resources for the year 2022.

Table 3 Indonesia's Energy Grid.

Energy sources	**Percentage**
Petroleum fuel (+Biofuels)	3.95%
Gas	17.16%
Coal	66.01%
Biofuels	0.77%
Water	6.90%
Geothermal	5.55%
Biomass	0.23%
Other EBT (wind, etc.)	0.19%

Results

The impact analysis conducted in this study adopts the CML-IA Baseline method, developed by the Center for Environmental Science at Leiden University. This methodology enables the assessment of various environmental impacts, including CO2 emissions, across the entire life cycle of EV and ICEV.

Figure 5 presents a visual representation of the results obtained from the CO2 emissions analysis for EV and ICEV throughout each of the respective life cycles. The diagram depicts the emissions generated at different stages, including production, transport, use phase, and end-of-life. By comparing EVs and ICEVs, the diagram highlights the disparities in emissions between the two vehicle types over the course of their entire life cycles.

This study reveals that an EV has a total emissions value of 70,996.48 kg CO2 eq, which is higher than the emissions from ICEV (60,451.21 kg CO2 eq). The use phase of the vehicles contributes significantly to the overall emissions. This indicates that during the operation of EV, the generation of electricity and its associated emissions play a significant role in the total environmental impact.

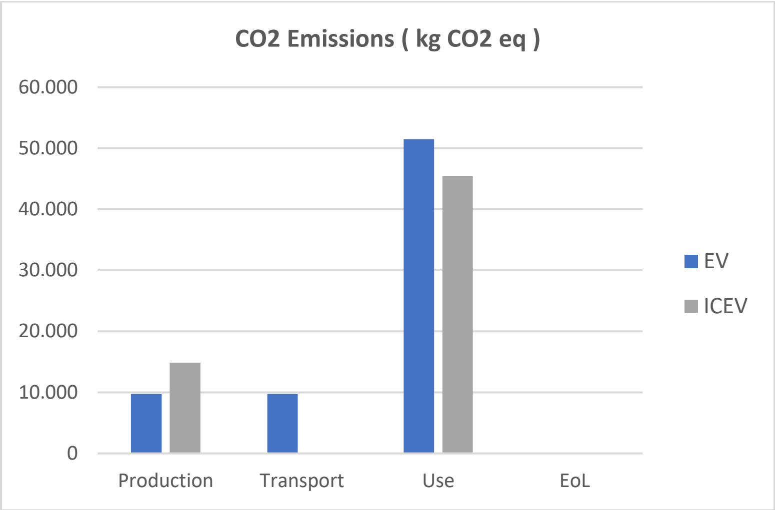

Figure 3 CO_2 emissions EV and ICEV

Part 2: System Dynamics Simulation

The system dynamics model was developed to investigate and quantify the adoption of EVs and its interactions with various related subsystems. This modeling approach enables a deeper understanding of the dynamic behavior and feedback loops within a system. To visually represent the interconnectedness and feedback mechanisms among different variables and components of the defined system, a causal loop diagram (Figure 4) was constructed. This diagram facilitates the visualization of the relationships and dependencies that influence the adoption of EVs, including factors such as government policies, the availability of charging infrastructure, consumer preferences, and technological advancements. By integrating these elements into the system dynamics model, researchers are able to simulate and predict the potential impacts of various scenarios and interventions on the adoption of EVs. This analytical tool provides valuable insights for policymakers, industry stakeholders, and researchers to make informed decisions and formulate effective strategies to promote the widespread adoption of EVs and achieve sustainable transportation goals.

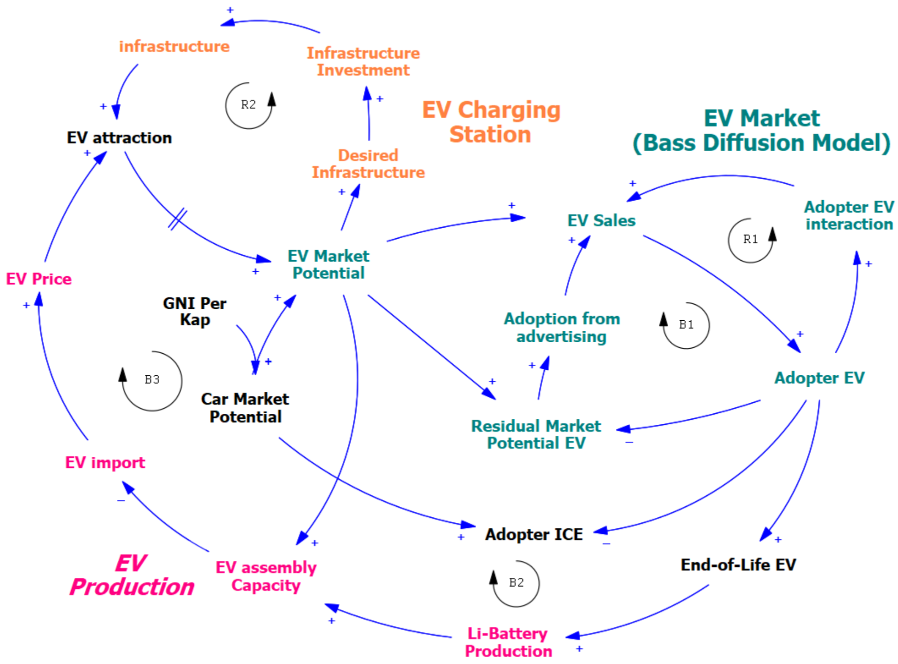

Figure 4 Causal Loop Diagram of EV Adoption Process

The causal loop diagram above illustrates the subsystems of the EV market, production, and infrastructure (EV charging stations). The diagram depicts five feedback loops. Two of these are reinforcing (positive) feedback loops, which means that variables reinforce each other. The remaining three are balancing (negative) feedback loops, which indicate that the subsystems self-regulate their conditions. R1 represents a feedback loop between EV Sales, adoption EV interaction, and Adopter EV. It explains how EV sales are influenced by the interaction among adopters. R2 represents a feedback loop involving the EV main infrastructure, specifically the charging station. B1 represents a feedback loop related to EV sales resulting from advertising efforts. B2 represents a balancing feedback loop that involves Li-Battery production, EV assembly capacity, EV import, EV price, EV attraction, EV market potential, EV sales, Adopter EV, and End-of-life EV. This feedback loop explains the relationship between EV production capacity, price, and sales. B3 represents a feedback loop originating from EV import, EV assembly capacity, EV attraction, and EV market potential. This feedback loop explains the impact of EV production capacity on the EV market potential.

The calculation of the number of adopters refers to the Bass Diffusion Model, which describes the adoption of new technology. The Bass Diffusion Model differentiates adopters of new technology into two groups: innovators and imitators. The Bass Diffusion Model is a mathematical model that predicts the cumulative number of adopters over time based on the influence of these two groups. It takes into account the potential market size, the innovators' influence, the imitators' influence, and the market saturation level.

The causal loop diagram visually represents the interrelationships and feedback loops between the EV market, production, and infrastructure subsystems. It shows how changes or variables in one subsystem can impact other subsystems and vice versa. The Bass Diffusion Model is incorporated into this diagram to capture the dynamics of EV adoption and its influence on the overall system.

By developing and analyzing this system dynamics model and causal loop diagram, researchers can gain insights into the factors that drive or hinder the adoption of EVs, understand the interdependencies between different subsystems, and identify leverage points for promoting the widespread adoption of EVs and the necessary infrastructure development [22]. The Bass Diffusion Model Equation can be shown as follows.

$$n_t = \frac{dN_t}{dt} = p(M - N_t) + q\frac{1}{M}N_t(M - N_t) \qquad (1)$$

where :

n_t= product purchases in period t

N_t= cumulative product purchases until the beginning of period t

M= cumulative market potential on the whole product life cycle

p= coefficient of innovation; q= coefficient of imitation

The imitation coefficient is derived from the adoption fraction and contact level values. The innovation coefficient indicates the proportion of individuals who are inclined to adopt a new product before others. In this study, the values of the coefficient of innovation is assumed to be 0.02 and 0.2 for the coefficient of imitation.

The simulation was conducted for a period of ten years from 2022 to 2032. Two policy scenarios were examined, namely the policy of reducing the price of EVs by 20% and the policy of increasing the rate of investment in EV charging stations. Based on the simulation results, the number of EV adopters can be observed in Figure 5.

As exhibited in Figure 5, the policy of increasing the addition of charging stations resulted in a 25% higher number of EV adopters compared to the policy of reducing the price of EVs. The simulation results show that in the year 2032, under the baseline scenario, there are approximately 1.39 million vehicles. By implementing the policy of reducing the price of EVs, the number of adopters increases to 1.56 million vehicles, and with the policy of increasing the addition of charging stations, it reaches 1.97 million vehicles.

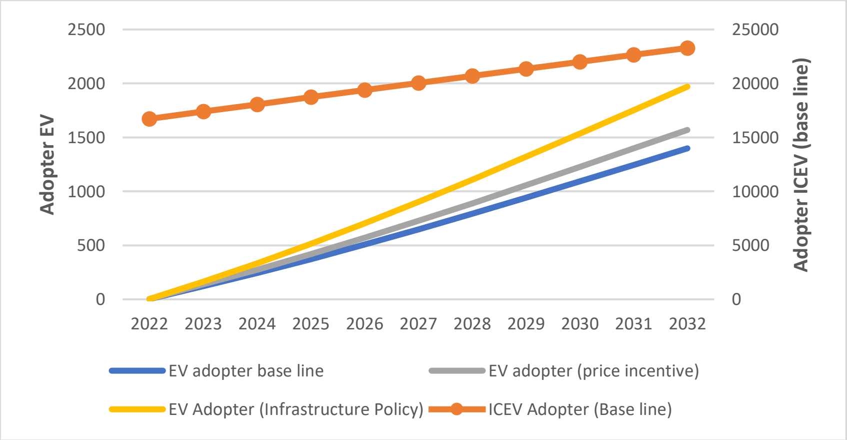

Figure 5 Number of EV and ICEV Adopters

Based on the previously calculated CO2 emission values, the total emissions generated by EVs and ICEVs can be calculated. Figure 6 shows the total CO2 emissions generated by EVs and ICEVs per year. Based on the calculation of total emissions, it is assumed that the number of vehicles produced and transported is equal to the number of vehicle purchases in that year.

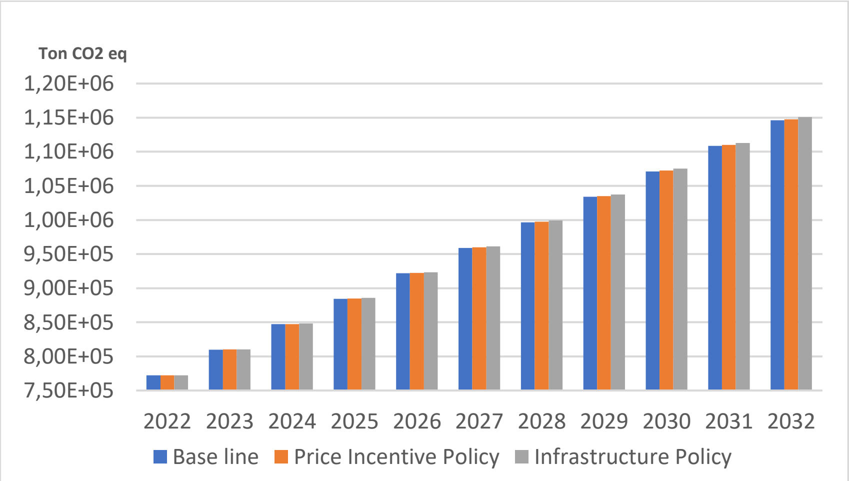

Figure 6 Total CO2 Emission from EV and ICEV

As expected, increasing the number of EVs cannot effectively reduce the total emissions generated. In 2032, based on the calculation of total emissions, it is 1,146,195,677 tons of CO_2 eq in the baseline scenario, 1,147,642,918 tons of CO_2 eq in the price incentive policy scenario, and 1,151,050,011 tons of CO_2 eq in the scenario of improving EV charging station infrastructure.

4 Concluding Remarks

The effectiveness of government initiatives aimed at reducing CO_2 emissions by promoting the use of EVs as a replacement for ICEVs may face limitations. This can be attributed to the substantial emissions generated throughout the entire life cycle of EVs, which can potentially exceed those of ICEVs. One of the primary contributing factors to this disparity is Indonesia's energy grid, which heavily relies on sources with high emissions. In order to realize the government's objectives of increasing the number of EV adopters, additional measures need to be implemented.

Policies that enhance the appeal of EVs can play a pivotal role in driving adoption rates. Factors such as price competitiveness and the availability of charging infrastructure are critical components that influence consumers' decisions to switch to EVs. Based on the simulation results, the policy of increasing the installation of charging stations for EVs has demonstrated the highest impact on the number of EV adopters.

The successful implementation of EVs as a means to effectively reduce CO_2 emissions in Indonesia is impeded by the current state of the country's energy grid, which predominantly relies on coal and other high-emission energy sources. To achieve substantial emissions reductions through widespread EV adoption, it is imperative for Indonesia to transition towards a greater reliance on clean and renewable energy sources for electricity generation.

This transition would not only contribute to mitigating CO_2 emissions but also foster a more sustainable and environmentally friendly transportation sector. Government-led initiatives, policy reforms, and investments in renewable energy technologies are essential for facilitating this transition and ensuring that the potential environmental benefits of EVs are realized in Indonesia.

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