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Evaluating the Environmental Impacts of Electricity Grid and Geographical Factors on CO_2 Emissions in Electric Vehicle Adoption

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ABSTRACT

The global interest in electric vehicles (EVs) to reduce CO_2 emissions requires understanding their emission-mitigating factors. This study investigates how electricity grid characteristics and geographical factors affect EV adoption and associated emissions. We address two questions: (1) Does a country's electricity grid significantly impact EV effectiveness in reducing CO_2 emissions? and (2) To what extent does the geographical factor of EV production influence emissions? Two methodologies are used to answer these QRs, namely life cycle assessment to calculate the CO_2 emission throughout EV life cycle subject to electricity grid and EV supply chain and system dynamics to simulate the impact of EV adoption on CO_2 emission reduction. The results will provide valuable insights for policymakers, enabling them to design effective strategies to promote sustainable EV adoption and maximize the environmental benefits of transitioning to electric mobility..

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

Introduction

The global electric vehicle (EV) stock has witnessed remarkable growth in recent years, with the number of EVs reaching 27 million units by 2022, marking an annual growth rate of 82.3% [1], [2], [3], [4]. This expansion is chiefly driven by surging EV sales in China, continental Europe, and the United States, establishing them as pivotal players in the global EV market. In 2022, China alone accounted for the highest EV population, with 13.7 million units, constituting 51% of the global EV population [5].

The promotion of EVs on a global scale primarily addresses two critical issues: reducing greenhouse gas (GHG) emissions and mitigating the depletion of fossil fuel reserves [5]. The adoption of EVs is expected to curtail CO_2 emissions and diminish reliance on fossil fuels to power conventional combustion engine vehicles. Electrification of road transportation is poised to reshape the future of mobility, bolster environmental sustainability, and revolutionize the energy landscape [6].

Numerous countries have implemented diverse policies to encourage EV adoption, often featuring tax exemptions for EVs and related equipment, purchase incentives, mandates, and deployment targets [5]. These initiatives extend beyond EV leaders, with many developing nations also embracing policies to bolster EV adoption. In Indonesia, government vehicles have been mandated to transition to EVs since 2022, while EV purchase subsidies were introduced in 2023. [5].

The increased adoption of EVs in several countries can be primarily attributed to the supportive policies enacted by their respective governments, aiming to incentivize and promote EV usage, making them more economically appealing and competitive against ICEVs. Through financial incentives such as tax credits, subsidies, and rebates, governments effectively reduce the initial purchase cost of EVs, rendering them more accessible to consumers.

The potential for substantial CO_2 emissions reduction through EV utilization in the transportation sector is acknowledged. Nevertheless, the efficacy of this reduction is constrained, particularly in nations heavily reliant on carbon-intensive electricity sources [7], [8]. A comprehensive evaluation of EV impact necessitates consideration of its entire lifecycle, transcending end-user perspectives. In Indonesia, electricity generation dominated by coal may limit emission reductions, and the growth of EVs could amplify electricity demand, potentially increasing CO_2 emissions from energy production and battery manufacturing. A holistic lifecycle assessment is imperative, encompassing raw materials, battery production, manufacturing, electricity generation, vehicle operation, and end-of-life considerations [9].

This study assesses the environmental impact of EV adoption in a country where the electricity grid is dominated by fossil fuels, as often found in developing countries like Indonesia. Additionally, it examines the environmental implications of localizing EV production, as Indonesia aspires to integrate into the global EV value chain by producing EV batteries.

EV Powertrain Technology

Powertrain technology encompasses the vehicle's integrated system for generating and transmitting power for propulsion. Advanced powertrain technologies prioritize efficiency enhancement, emission reduction, and the integration of alternative fuels and electric propulsion to align with contemporary transportation's environmental and performance objectives. EV powertrain technology is important in modern transportation, especially within sustainable and eco friendly mobility. In EVs, the powertrain substantially differs from traditional ICEV, comprising three primary components: the electric motor, battery pack, and power electronics and control systems [10], [11].

EV powertrain technology offers key advantages, including zero tailpipe emissions, decreased reliance on fossil fuels, and reduced operational costs due to fewer moving components and heightened energy efficiency. As technology progresses, EV powertrains become increasingly cost-effective, offering extended ranges, faster charging capabilities, and deeper integration with renewable energy sources. Various types of EVs have been developed based on their energy sources [12]: Battery Electric Vehicle (BEV), Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Fuel Cell Electric Vehicle or FCEV [13], [14].

Life Cycle Assessment (LCA)

According to Farjana et al. [15], LCA is a comprehensive, quantitative analysis of environmental and social impacts across the entire life cycle of products, processes, or systems. LCA employs life cycle thinking, considering environmental, economic, and societal consequences. ISO 14040:2006 and ISO 14044:2006 provide the principles and frameworks for LCA, encompassing four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. LCA calculates a product's impact on specific factors throughout its life [16], [17], [18]. Figure 1 schematically describes the LCA method framework.

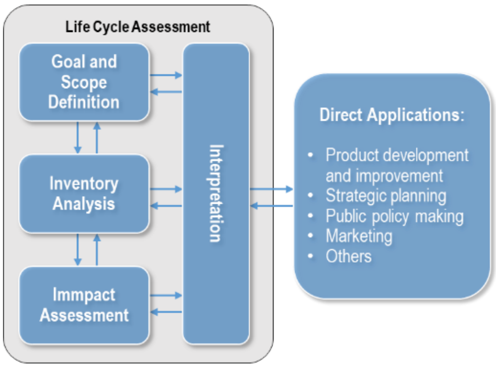

Figure 1. LCA method framework (ISO 14040) [17]

Measurement of EV Impact over ICEV

In addition to comparing CO_2 emissions generated by EVs and ICEVs during their life cycle, three measures will be calculated to exhibit the impact of EV adoption [1]. The measures are as follows.

(1) **Distance of Intersection Points (DIP)** represents the estimated number of kilometers that would need to be driven by an EV and the comparison ICEV so that the total life-cycle emissions of each vehicle type would be equal. The can be calculated using the following formula:

$$DIP = \frac{PE_{ev} - PE_{icev}}{\left((WTW_{icev} + M_{icev}) - (WTW_{ev} + M_{ev})\right)} \tag{1}$$

where PE_{ev} and PE_{icev} are the production emissions in tons of CO_2eq for the EV and ICEV respectively. The WTW_{icev}/WTW_{ev} and M_{icev}/M_{ev} are the Well-to-Wheel (WTW) and maintenance (or use phase of the vehicles) GHG emissions ICEV or EV in tons of CO_2eq per kilometer.

(2) **Emission Disparity (ED)** represents the difference in life-cycle emissions at a specific distance driven. It estimates the life-cycle emissions from the production and use phases at the end of the studied vehicles' lifetimes. The ED in tons can be calculated using the following formula:

$$ED = (PE_{icev} + (WTW_{icev} + M_{icev}) * LT + EOL_{icev}) - (PE_{ev} + (WTW_{ev} + M_{ev}) * LT + EOL_{ev}) \tag{2}$$

Most inputs are similar to those of Formula (1), with the addition of LT, the estimated lifetime of the vehicle measured in kilometers, and EOL_{icev} and EOL_{ev}, representing the EOL emissions associated with each vehicle's recycling/ disposal process type.

(3) **Maximum Production Emission (MPE)** estimates the lowest level of production emissions of an EV necessary for an EV to be considered a mitigation solution over the EV's comparative life cycle and the compared ICEV. The MPEs, measured in t CO_2eq, can be calculated as follows.

$$MPE = (PE_{icev} + (WTW_{icev} + M_{icev}) * LT + EOL_{icev}) - ((WTW_{ev} + M_{ev}) * LT + EOL_{ev}) \quad (3)$$

System Dynamics

Systems Dynamics involves managing dynamic behavior in controlled systems [19], [20]. It focuses on influencing controllable components within systems that exhibit interrelationships and dynamic behavior. The method employs model simulations to achieve objectives, describing system structures through variables, their relationships, and model parameters. Powersim Studio 10 software assists in simulating System Dynamics Models, employing mathematical relationships and basic functions like delay, smoothing, and tables to elucidate system component connections. A clear definition of the relevant system and conceptual model is essential before creating the simulation model structure [20], [21], [22], [23].

Research Method

This study comprises two main components. Firstly, an LCA of EVs (limited to BE) is conducted to quantify the CO_2 emissions throughout an EV's lifespan compared to ICEVs. OpenLCA software is employed, utilizing data from the well-established Ecoinvent database that is widely used in LCA studies. The second part involves a system dynamics model to simulate the adoption progress of EVs and ICEVs over time. This simulation utilizes the LCA output to calculate the CO_2 emissions of the entire population of EVs and ICEVs as their adoption rates evolve within the specified time frame. The Bass diffusion model is applied to estimate EV population growth. Powersim Studio 10 software facilitates the simulation of the system dynamics model.

Life Cycle Assessment (LCA) of EV and ICEV
Goals and Scopes

In LCA, "scope" defines the specific boundaries that distinguish the components of the system under study from those external to it. This study's scope encompasses the complete life cycle (cradle-to-grave) of EVs and ICEVs, as illustrated in Figure 2. The study addresses the following system boundaries: the input of raw materials for EV and ICEV production and the four primary processes within their supply chains, including production, transportation, use phase, and end-of-life. Figure 2 visually represents this system boundary and outlines the four key processes involved in the life cycle of both EVs and ICEVs.

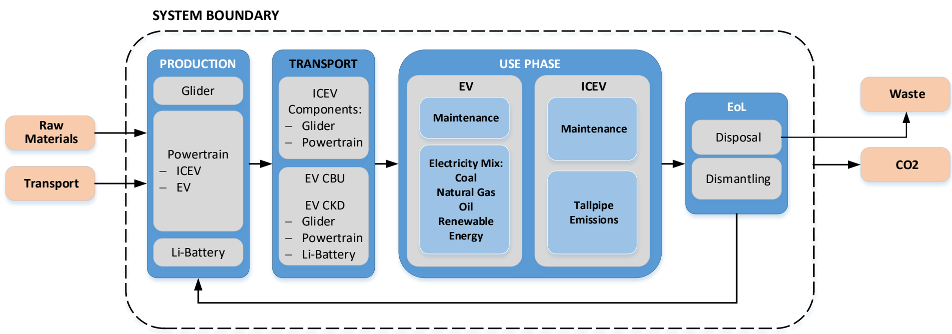

Figure 2. System Boundary

Life Cycle Phases
Production Phase

Waste EoL Disposal Dismantling CO_2 The production phase for both EVs and internal ICEVs consists of two key elements: the glider and powertrain, and the Lithium-ion (Li-ion) Battery. The glider encompasses the vehicle frame, while the powertrain is the vehicle's driving force. In EVs, the primary energy source is the Lithium-ion Battery. EV production utilizes three schemes: Completely Built-Up (CBU), Completely Knocked Down (CKD) 1, and CKD 2. CKD 1 involves a local final assembly process with imported EV batteries and powertrains. At the same time, CKD 2 entails a final assembly process with local production of EV Li-ion batteries and powertrains, while some EV powertrain components remain imported.

Transport Phase

The transport phase involves transferring vehicles from production facilities to wholesalers, utilizing two modes: sea transport via container ships and land transport via trucks. Sea transport is employed explicitly for importing electric vehicles.

Use Phase

During the use phase, ICEVs produce direct CO_2 emissions in the case of ICEV, while EVs increase the demand for electrical energy as their primary power source. The emissions generated from EVs in this phase include the impact of 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

Relevant data collection relies on prior studies and datasets from the Ecoinvent Database. Data for the life cycles of EVs and Internal ICEVs in the Ecoinvent database originates from Habermacher's research [14]. In the Indonesian market, the Hyundai Kona EV and Hyundai Ioniq EV were top-selling EVs in 2021, with the Hyundai Ioniq EV chosen as the reference vehicle for LCA in this study. The 2019 Hyundai Ioniq EV boasts a consumption rate of 0.138 kWh/km and a range of 311 km, per the Worldwide Harmonized Light Vehicles Test Procedure. A mileage assumption of 150,000 km, commonly used in prior research, is applied. South Korea dominates EV exports to Indonesia, accounting for 58% of total imports, with Japan, Germany, and the UK also contributing.

During the usage phase, conventional vehicles produce direct CO_2 emissions or tailpipe emissions. In traditional vehicles, internal combustion engines emit CO_2 directly as fuel undergoes combustion, contributing to the overall emissions during use. On the other hand, electric cars rely on electricity as their primary power source and do not have direct vehicle emissions. However, their use increases electricity demand, leading to electricity generation emissions. These emissions depend on the type and energy source used by power plants.

System Dynamics Simulation

The system dynamics model was created to analyze and quantify EV adoption and its interactions with related subsystems. Figure 3 illustrates the causal loops within the model. The diagram portrays the subsystems of the EV market, production, and infrastructure (EV charging stations). It exhibits five feedback loops, two of which are reinforcing (positive) feedback loops, signifying that the variables mutually reinforce each other. The other three balance (negative) feedback loops, indicating that the subsystems autonomously regulate their conditions.

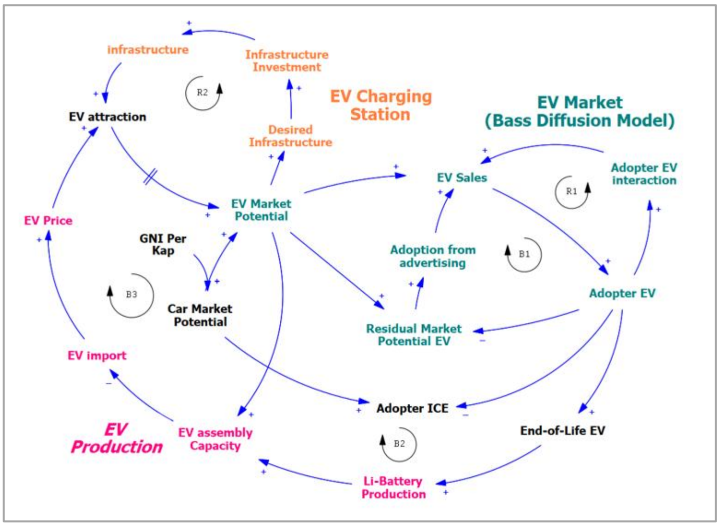

Figure 3. Causal Loop Diagram of EV Adoption Process

The model was focused to estimate dynamically the market potential of vehicles, the number of EV adoption and ICEV population and subsequently the CO_2 emission as the EV adoption grows. The of market potential of vehicles was estimated using the following formula:

$$No. of\ vehicles\ (1000\ unit) = GNI\ per\ cap \times 14{,}637 - 110{,}74 \qquad (4)$$

The parameters in the formula were estimated using data of GNI per capita [24] and Passanger Cars in use (The Central Bureau of Statistics, 2023) with coefficient determinant of 91.52%. The number of EV adopters was estimated using the Bass Diffusion model, with innovation and imitation parameters estimated using the approach developed by Massiani & Gohs [25]. Data of EV sale from January 2020 – November 2022 was used to calculate the parameters [26]. Number of ICEV adopters was calculated using the following equation.

$$Jumlah\ Adopter\ ICEV = Potensi\ Pasar\ Mobil - Jumlah\ Adopter\ EV \quad (5)$$

Results And Discussion

Impact of production location schemes

The LCA results reveal that over the entire life cycle (150,000 km), an Internal ICEV produces 46.58 tons of CO_2eq, while EVs with CBU, CKD1, and CKD2 schemes emit 16.03, 20.99, and 23.56 tons of CO_2eq, respectively. During the use phase, both ICEVs and EVs emit 0.26 kg and 0.11 kg of CO_2eq per kilometer, regardless of production scheme. In both ICEVs and all EV production schemes, the use phase contributes the most to CO_2 emissions in the respective countries where the vehicles are operated. In the baseline scenario, the use phase of EVs accounts for 99.2%, 75.8%, and 67.5% of CO_2 emissions for CBU, CKD1, and CKD2 schemes, while the use phase of ICEVs contributes 83.9%.

Expanding EV production activities in the host country leads to increased CO_2 emissions from production, raising the total CO_2eq and the production phase's contribution to CO2eq generation. Compared to the CBU scheme, CO_2 emissions increase by 31% and 47% for CKD1 and CKD2 production schemes, respectively. Figure 5 presents a comparative overview of CO_2 emissions in each phase of the vehicle life cycle for different EV production schemes. Fiure 4 presents the comparison of total CO_2eq emission of ICEV and of EV for CBU, CKD1 dan CKD2 production schemes.

Among the various production schemes, only CKD2 results in a higher level of CO_2eq emissions during the production phase. For CKD2, the Direct Impact Potential (DIP) is 1,138 km, the Manufacturing Process Emissions (MPE) amount to 30.48 tons of CO_2eq, and the Embodied Emissions (ED) reach 23.02 tons of CO_2eq. In comparison to assessments of EVs' mitigation potential for CO_2 emissions compiled in a review and meta-analysis by Dilman et al. (2020), the estimated DIP (thousand km) ranges from 16.98 (Iceland) to 91.02 (Latvia), while the estimated MPE (tons of CO_2eq) ranges from 4.28 (Latvia) to 39.53 (Iceland), and the estimated ED ranges from 15.08 (Latvia) to 50.33 (Iceland).

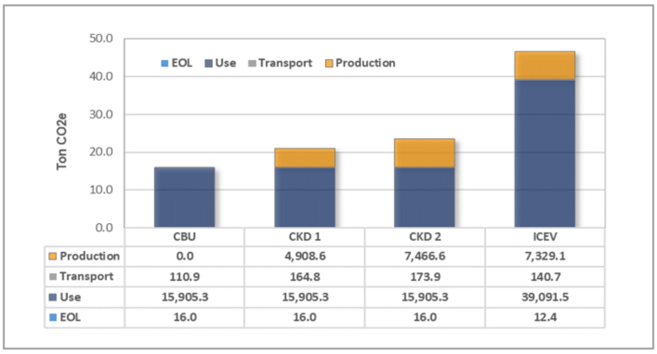

Figure 4. Total CO_2eq emission of ICEV and of EV for CBU, CKD1 dan CKD2 production schemes

Among the various production schemes, only CKD2 results in a higher level of CO_2eq emissions during the production phase. For CKD2, the Direct Impact Potential (DIP) is 1,138 km, the Manufacturing Process Emissions (MPE) amount to 30.48 tons of CO_2eq, and the Embodied Emissions (ED) reach 23.02 tons of CO_2eq. In comparison to assessments of EVs' mitigation potential for CO_2 emissions compiled in a review and meta-analysis by Dilman et al. (2020), the estimated DIP (thousand km) ranges from 16.98 (Iceland) to 91.02 (Latvia), while the estimated MPE (tons of CO_2eq) ranges from 4.28 (Latvia) to 39.53 (Iceland), and the estimated ED ranges from 15.08 (Latvia) to 50.33 (Iceland).

Impacts of Electricity Grids

The impact of eectricity grid on CO_2 emission is shown in the following figure.

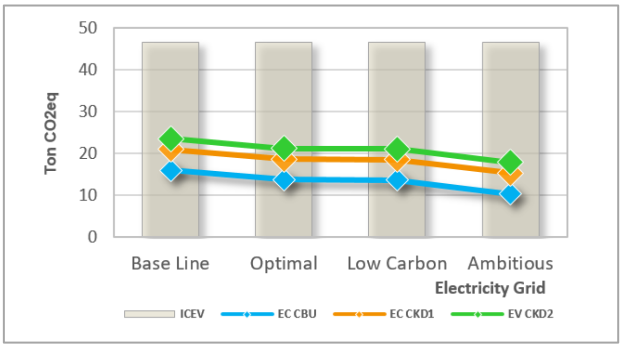

Figure 5. The impact of electricity grid on CO_2 emission of EV On CBU, CKD1 and CKD2 in comparison to ICEV

However, for the CKD1 and CKD2 schemes, the reduction in CO_2 emissions due to increased NRE use is less pronounced than the CBU scheme. As EV production activities expand, more CO_2 is generated during the production phase, gradually diminishing the impact of increased NRE utilization in mitigating CO2 emissions. For CKD1, the effects of NRE increase on CO_2eq mitigation is 11.3%, 11.9%, and 27.2%, while for CKD2, it is 9.9%, 10.4%, and 24.3% for the Optimal, Low Carbon, and Ambitious scenarios, respectively.

Impacts of EV Promoting Policies

Two levers were applied to EV-promoting policies: financial subsidies for EV purchases and financial incentives for charging station investors. The combination of these two levers formed four scenarios, as described in Table 1.

Table 1. Model Parameters for EV Promoting Policies

Scenario	Incentive Parameter	
	Battery charging Station Investment	EV Purchase Price
Scenario 1	1	1
Scenario 2	1	0.7
Scenario 3	2	1
Scenario 4	2	0.7

The impact of EV promoting policies on government targets can be summarized as follows (Table 2).

Table 2. The Impact of EV promoting policies

Target	Scenario 1	Scenario 2	Scenario 3	Scenario 4
No. of EV Adopters	Not achieved	Not achieved	Not achieved	Achieved
No. of charging stations	Achieved	Achieved	Achieved	Achieved

Supporting by EV promoting policies, number of EV adopters are increasing regardless the policy scenarios, however, only Scenario 4 can achieve the government targets on number of battery charging stations and number of EV adopters. Based on Scenario 4, the emission of total CO_2 emission per year on low carbon scheme of electricity grid is depicted in Figure 6.

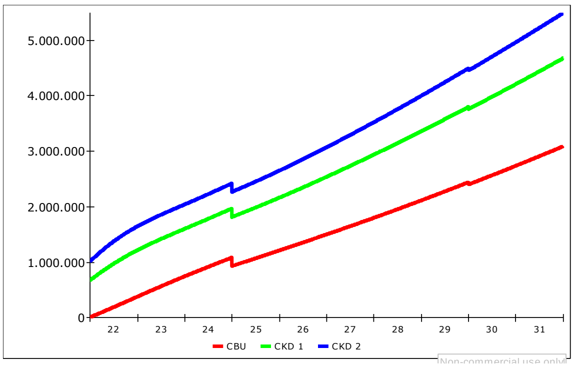

Figure 6. Total CO_2 emission per year based on Scneario 4 and Low Carbon scheme of electricity grid

Conclusion

Based on the LCA results, ICEVs produce higher CO_2 emissions than EVs throughout their lifecycles, with the use phase being the largest contributor. As EV production activities expand in the host country, CO_2 emissions increase from both the use and production phases.

The replacement of NRE usage has the potential to reduce EV emissions. Promoting EVs through two levers— incentives for battery charging station investments and EV purchase prices—can drive the number of charging stations and EV adopters to meet government targets. However, these targets remain relatively small compared to the ICEV population, hence, CO_2 emissions are expected to continue rising in the coming years.

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