Evaluating the Damage Cost of Vehicle to Grid Integration in Indonesia Power Grid for Sustainable Energy System

Priyo Adi Sesotyo
Department of Electrical Engineering, Universitas of Semarang, Semarang, Jawa Tengah 50196, Indonesia

Abstract: The cost incurred in the EV Charging is currently only from the energy consumed consideration. While there is extensive research on the impact of EV charging on grid infrastructure and operation, few studies quantify these effects in terms of explicit 'damage costs'. However, besides energy problems, the analysis of the environmental impact of EVs has not been quantified monetarily. This paper aimed to investigate the damage cost (DC) of EVs in comparison with Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) based on Indonesia Java Bali's grid conditions. Using the existing data in Indonesia, the characterisation parameter were determined using cradle-to-gate life cycle analysis (LCA) and ReCiPe 2016 then converting the endpoint indicators impacts to DC using a monetary weight factor (MWF) of those two EVs. Cradle to gate LCA is a method for evaluating the environmental impact of battery from the extraction of raw material to the factory gate and ReCiPe 2016 is a widely used of LCA method, which converts emission and resources extraction into certain indicators. Results show that DC for a 20 kWh BEV = 0.12 ± 0.01 USD/kWh compared to an 8 kWh PHEV = 0.08 ± 0.005 USD/kWh. Therefore, the DC of an extra 0.02 USD/kWh for BEVs and 0.015 USD/kWh for PHEVs should be considered in formulating the EV charging tariff.

Keywords: Battery Electric Vehicle, Cradle to Gate LCA method, Damage Cost, Monetary Weight Factor, ReCiPe 2016 method.

Correspondents Author:
Priyo Adi Sesotyo, Department of Electrical Engineering, Universitas Semarang, Indonesia
Email: psesotyo@usm.ac.id

Received May 8, 2025; Revised May 17, 2025; Accepted May 17, 2025; Published May 18, 2025

Introduction

As Indonesia accelerates its transition toward sustainable transportation, electric vehicles (EVs) are increasingly positioned as a cornerstone of its low-emission mobility strategy. Government incentives, investment in charging infrastructure, and growing public interest have collectively spurred the adoption of EVs across the archipelago. However, while environmental benefits such as reduced tailpipe emissions are widely recognised, the broader environmental and economic externalities associated with EV charging remain insufficiently addressed—particularly in electricity generation in Indonesia, which still relies heavily on fossil fuels. By the time the term vehicle to grid (V2G) was proposed by Kempton and Letendre (Kempton et al., 2001), it had astonished the public with its purpose of utilizing the electric vehicle (EV) battery as a further level of electric storage. Numerous EV fleets at various charging locations need a comprehensive analysis of suitable distributed energy resources (DER). Various DERs are penetrating the current grid, which needs to adapt to ancillary services, covering the grid code regulation, power quality improvement, voltage regulation, and load shifting (Choi et al., 2016). DER is expected to overcome the old-fashioned ancillary service by advancing power electronics composed of electrochemical batteries. Eventually, one of the DER advanced technologies, V2G, is known by auto manufacturers, utility companies, and EV owners, especially for plug-in electric vehicle (PHEV) and battery electric vehicle (BEV) model types. One crucial yet under-explored dimension is the environmental damage costs incurred during the EV charging process, especially when electricity is sourced from coal-fired power plants. These damages include greenhouse gas emissions, particulate matter, acidification, and human health impacts factors that could significantly offset the perceived benefits of EV adoption. Monetizing these externalities is vital for establishing a more comprehensive cost-benefit analysis of EVs and for informing policies that ensure a truly sustainable transition.

The integration of EVs provides ancillary services, improving power system stability, decreasing the operational load on protection relays, and potentially lessening the impact of various contingencies. The service comprises short-term high-cost power generation operation, which flow to balance the variable load fluctuation and accommodate unexpected equipment failures (Sortomme, 2012). V2G can put EVs as the personal emergency power supply whenever there is an outage in the residential from the grid. Various obstacles embrace the V2G implementation: (i) the depletion of battery lifetime because of its more frequent cycles or over-discharge of the batteries (Arfeen et al., 2021), (ii) the improvement of communication appliances like smart meters (advanced metering infrastructure-AMI) and (iii) real-time pricing framework in the grid authority (Sesotyo et al., 2024a). V2G technologies facilitate the EVs to charge from the grid and supply power back, employing discharging power to the grid at peak load or higher demand. If implemented, the best estimation for the capability of V2G can contribute up to two-thirds of the forecasted peak load (Sioshansi & Denholm, 2010). Acting as the ESS: The EV battery enables bi-directional power flow, acting as the onboard energy storage system. The principle of V2G infrastructure comes at the EV communication with the power grid when not in use, provides power during peak load requirements, and gets charged from the grid during off-peak hours. The concept is to build an exchange system between the grid and the EV with ESS capabilities to benefit both parties (Briones et al., 2012). Kempton et al. (Kempton et al., 2001) observed that 92% of the total EVs fleet remains parked even during peak hours. Whenever EVs is idle, they should be connected to the EVCS (EV charging station). The connection enacts onboard batteries from EVs via an appropriate communication device that will communicate to the AMI to provide load shedding, peak shaving, and many other features (Pani et al., 2015).

V2G will probably play a significant role in decarbonizing land transport and electrical systems regarding fuel combustion (Catapult & Zero, 2020). Greenhouse gas (GHG) emissions of CO2 from fuel combustion make up one-quarter of the global total. Global energy consumption in 2019 was dominated by the energy and transportation industries, which accounted for approximately 72% of total consumption; the energy industry's share was 46%, while the transportation industry's share was 26%. Government initiatives, such as Presidential Regulation No. 55/2019 on Battery Electric Vehicles, aim to accelerate EV adoption by offering tax incentives, building domestic battery industries, and expanding charging infrastructure. As of 2024, EV sales continue to rise, and public and private investments in charging stations are expanding across major cities. However, while attention has been given to the infrastructure and policy frameworks necessary to support EV deployment, the environmental implications of EV electricity consumption particularly in relation to Indonesia's fossil-fuel-dominated power grid—have received limited scrutiny. Regarding energy efficiency, EVs considerably outperform conventional fuel-powered cars. The overall efficiency of electric vehicles is 48%, a substantial increase from the roughly 25% efficiency of internal combustion engine vehicles. The integration of EVs will increase the load profile on Jawa Bali's power grid, Indonesia's largest, which in 2019 accounted for 75% of total energy sales and 61% of generation capacity, exhibiting a peak load of 28,291 MW, a load factor of 80%, and an energy requirement of 180.8 TWh (Directorate of Corporate Planning, 2021). Coal-fired power plants make up 59% of the energy sector, with renewable energy sources comprising the remaining 9%, of which solar photovoltaic power plants account for 1% (Directorate General of Electricity, 2022). In regions where electricity generation is predominantly fossil-fuel-based—as in Indonesia, where over 60% of electricity still comes from coal—the indirect emissions associated with EV charging can be substantial. These emissions contribute to climate change, human health impacts, and ecosystem degradation.

Widespread adoption of electric vehicles (EVs) significantly increases electricity demand during peak charging periods, potentially destabilizing the power grid. Conversely, effective charging and discharging management would enable EVs to function as substantial energy storage units, potentially bolstering grid stability (Huda et al., 2019). Thus, EV charging and discharging management will soon become important in developing a smart system with mobile energy storage. Coal's environmental risks demonstrate spatial heterogeneity. Coal-fired power plants' air pollution disproportionately impacts some communities, whereas others experience groundwater contamination from mining operations (Ami et al., 2007). However, the environmental consequences of coal use are a matter of collective concern, as its extraction and combustion release greenhouse gases. Anthropogenic carbon dioxide emissions are the primary driver of global warming and climate change. The release of emissions from the power plant stack, potentially leaching into surrounding landfills, groundwater, and surface waters, poses risks to drinking water quality, human health (including cardiovascular disease and cancer), and aquatic life.

The fewer subsidies would negatively impact to the grid. During: Weekday and weekend, load levelling, plus frequency stabilisation, are achieved through V2G use (Huda et al.,2018). From the perspective of EV owner, V2G can reduce the cost of charging by up to 60.15%, and from the Grid Authority perspective, V2G potentially improves annual revenue by 3.65% for the replacement of the fuel (Huda et al., 2020). The profitable V2G scheme relies on the battery ageing cost and profile, and the electricity price ranges over time (Schwenk et al., 2021). One key point regarding V2G technology, whether preferable, is the battery degradation cost. The battery swapping service method can reduce costs instead of scheduling the battery charging (X. Li et al., 2022). While V2G applies to EVs, certain battery indicators will be abnormal, such as temperature reaching its threshold, and state of charge (SOC) calculation will be abnormal, leading to overcharging or over-discharging, which may further into system collapse. Aside from the grid, the EV penetration should have impacted the environment. Meanwhile, discussed increasing energy profit and reducing emissions from EVs, and Steen had compared different battery technologies for their lower environmental impact (Steen, 1999). While Sufyan et al., had emphasises that GHG emissions will slightly decrease despite the broader spread of EV utilization (Sufyan et al., 2020), Office of Energy Efficiency and Renewable Energy introduces the damage value from a person possibly affected by environmental impact (Office of Energy Efficiency and Renewable Energy, 2017). The ecological footprint of EV charging, developed by Murakami et al., stated that a combination of electric sources, especially with the help of vRE, may reduce the impact by approximately 10% (Murakami et al., 2018). While several studies in high-income countries have quantified and monetize such charging-related damage costs using life cycle assessment (LCA) and damage cost (DC) models, there is a significant research gap in the Indonesian context. Current literature largely focuses on EV adoption rates, infrastructure development, and consumer behaviour, with minimal emphasis on the hidden environmental costs of EV charging. Existing models often cannot reflect the unique characteristics of Indonesia's electricity mix, regional disparities, and socio-environmental priorities.

Several international studies have demonstrated that the environmental benefits of EVs depend highly on the electricity generation mix used during charging. For instance, research in the United States and China shows that when EVs are charged using electricity from coal-dominated grids, the resultant emissions of CO_2, NO_x, SO_2, and particulate matter can lead to significant health and environmental damages (Holland et al., 2016, 2021). In these studies, life cycle assessment (LCA) models are often used with monetization techniques—such as a social cost of carbon (SCC) and ReCiPe endpoint methods—to estimate the damage costs associated with each kWh of electricity consumed. In Indonesia, limited LCA studies have focused on the emissions of EVs during their operational phase, but few have extended their scope to include the monetization of associated damage costs. Given the country's continued reliance on coal (accounting for over 60% of electricity generation as of 2023), there is a substantial risk that EVs may shift environmental burdens rather than reduce them outright.

Currently, there is no specific method to calculate the economics of climate change, monetizing the environmental impact of the V2G. Monetization of environmental damage is a crucial step toward internalizing externalities in policy and market mechanisms (Wang & Tang, 2022). Tools such as ReCiPe 2016 translate emissions into damage endpoints (e.g., human health, ecosystem quality, resource depletion) and then assign economic values to these impacts. These methods have been widely used in Europe and North America to inform environmental product declarations (EPDs), carbon pricing, and sustainable procurement. In the EV sector, such monetization can inform true cost accounting of transportation modes, support the design of differentiated electricity tariffs, and encourage cleaner energy sourcing (Chen et al., 2021).

In Southeast Asia, however, these models are rarely applied with localized parameters. Indonesia lacks region-specific damage factors for air pollution, health costs, and ecosystem degradation, which limits the accuracy and policy relevance of imported models. National policy frameworks do not yet incorporate damage cost-based assessments in their cost-benefit analyses of EVs or electricity production.

Within this research, we evaluate a cost that monetizing the damage caused by V2G implementation, to apply to the cost of charging and discharging for the EVs with V2G technology applied within Indonesia Power Grid for Sustainable Energy System. The cost will include the damage cost across diverse EV capacities and GHG emissions within the monetary weighting factor (MWF) and deteriorate cost. Researchers use the ReCipe (Breetz & Salon, 2018; Notter et al., 2010) method to weigh a single impact regarding the public interest when comparing the approach to the product's environmental impact.

This gap presents both a challenge and an opportunity: without localised data on charging-related damage costs, policymakers risk underestimating the full environmental burden of electrified transport. Therefore, a systematic effort to quantify and monetize the environmental damage costs of EV charging in Indonesia is essential for developing effective pricing mechanisms, regulatory frameworks, and sustainable energy policies. This study aims to develop the V2G damage cost within Java-Bali's grid system using the MWF analysis approach. The EV owner and Grid Authority have to bear the damage cost in the EV charging tariff formulation because of the environment to develop a more sustainable ecosystem and fair rates for the stakeholders. The rest of the paper is organised as follows. The research's materials and methods are discussed in Section 2. Section 3 extends the analysis with results and discussion. Section 4 is a conclusion.

Material and Method

The overall material and method workflow will be as follows: data acquisition, LCA characterisation, endpoint monetization and the last will be EV damage cost calculation.

Material

Electric cars come in various forms, such as battery electric vehicles (BEVs) and plug-in hybrid electric vehicles. (PHEVs). We pay great attention to the use of batteries in 2 types of EVs, namely PHEV and BEV, as shown in Fig. 1. While PHEVs feature a battery and a conventional petrol or diesel engine, BEVs are powered by batteries. PHEVs can go a certain distance on electric power alone before the petrol engine takes over (Z. Li et al., 2019).

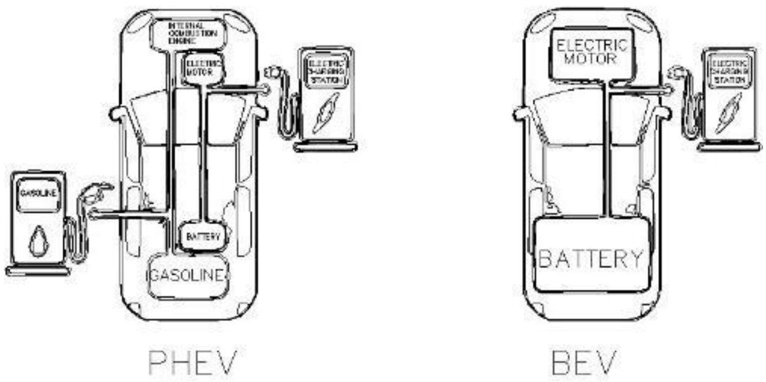

Figure 1 Illustration of PHEV vs BEV

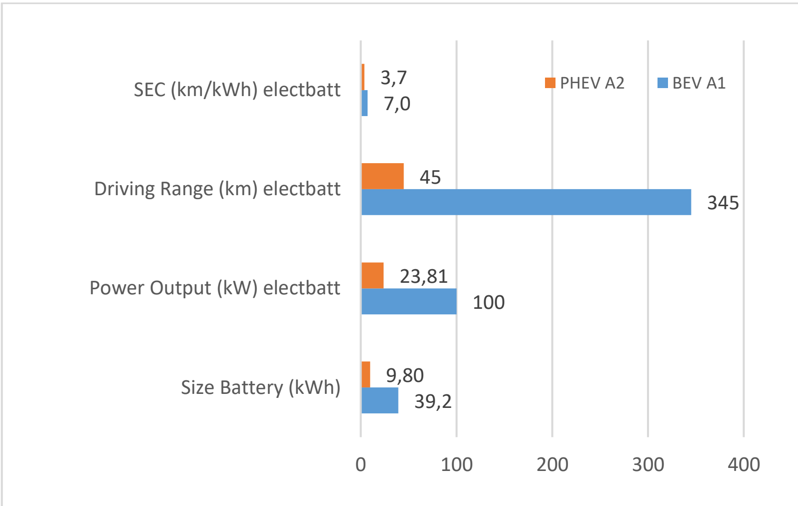

Figure 2 Comparison of BEV and PHEV as described in Fig.1

Also, we have constructed the specification comparison among common BEVs found in Indonesia, as indicated by A1, B1, C1, D1 and E1 in Fig. 3.

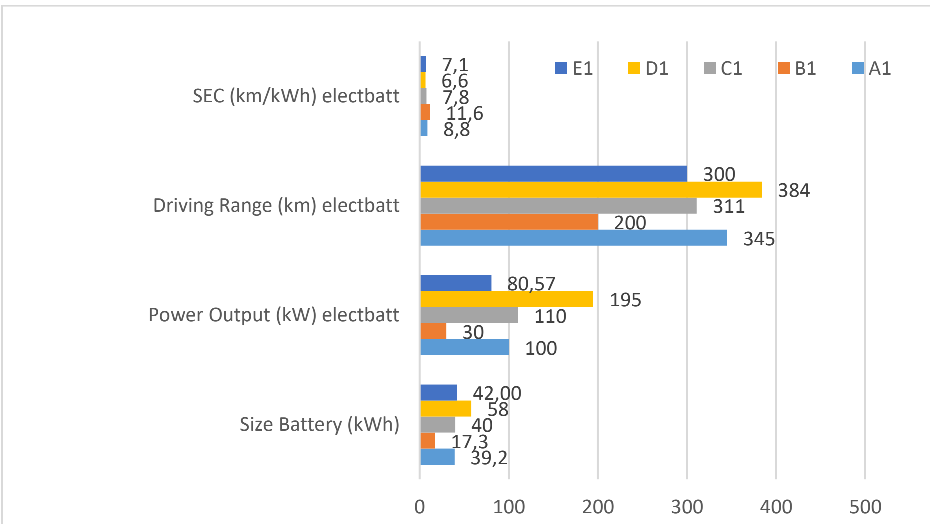

Figure 3 Comparison of common BEV found in Indonesia

The batteries account for about 30-40% of the BEV price, and the cost of the materials that make up the battery covers approximately 77% of the battery. Researchers simplified LiB lifespan by limiting its remaining capacity to 80%, thus setting the depth of discharge at 20%. The BEV and PHEV comparison used the energy from the depth of discharge (DoD) of 20% of the battery capacity (Xiong et al., 2020), see Table 1, to energize the motor drives until a certain distance was reached. DoD has the opposite relation with the number of charging cycles. In PHEV, they prioritize the use of batteries, and when the battery has reached its usage limit, they continue with the fuel engine, see Table 2.

Table 1 BEV Assumption (Sufyan et al., 2020)

Component Parameter	Unit	Value
SOC min/max	%	80/100
$P^{ev}_{ch,max}$	kW	20
$P^{ev}_{dch,max}$	kW	8
Drive Efficiency	%	90

Table 2 PHEV Assumption (office of energy efficiency and renewable energy, 2017)

Component Parameter	Unit	Value
Fuel	-	Pertamax
Engine Efficiency	%	30

Method

The EV battery research framework uses the two method LCA : (1) cradle to gate, as the method for evaluating the environmental impact of a battery up to be assembled into the EV, (2) ReCiPe 2016 method for evaluating the environmental impacts of products and processes through endpoint indicators, that linked to the long-term damage cause by environmental impacts. The comparison between two EVs charging, namely BEV and PHEV, with parameters CO_2 Emission Factor, Environmental Cost, and Damage Cost, can be seen in Fig. 5. Specific Energy Consumption (SEC) in units of kWh/km calculation on EV can be done with the following formulation:

$$\mathbf{SEC} = \frac{\mathbf{BattCap} * (\mathbf{1} - \mathbf{SOC})}{\mathbf{Distance}} \qquad (1)$$

With BattCap, the battery capacity (kWh), SOC (%), and distance (km). The Research Flowchart, shown in Fig. 4, will guide us in determining the Damage Cost and Profit for the respective EV type and EV Battery Charging. Aside from the SEC, there is an emission factor for certain EV that must be concerned about.

$$\mathbf{Emission = EF * BattCap} \tag{2}$$

EF stands for Emission Factor (gr CO2 eq / kWh) and Emission (gr CO2 eq).

$$\mathbf{EC = EC_{WF} * Emission} \tag{3}$$

EC stands for Environment Cost (USD/year), ECWF stands for EC weighting factor, which can be found in Table 7. Weighting is essential to converting the various environmental impacts into a known indicator using numerical factors based on the unit and value chosen. Within specific steps in the Life Cycle Assessment (LCA) method, weighting is frequently used because of its manageability and comprehensibility (ISO 14040 2006; ISO 14044 2006). LCA quantifies the environmental impact of a typical product's entire life cycle, whether hardware or software. In contrast, it is connected to abundant substance emission and resource exploitation, which can critically vary in environmental relevance. At the endpoint level, the assessment methods are classified by multiplying the value per damage unit and the result of endpoint characterization. Economic assessments result in monetary values, thus making them easy to understand and communicate and allowing their application to cost-effectiveness analyzes. A method for converting environmental impacts resulting in health damage and an ecosystem decline into economic values is described by Murakami et al. (2018).

With the help of LCIA, the interpretation of those LCA studies translates into a limited number of environmental impact scores (Klöpffer et al., 2015). Characterization factors, as means of LCIA translation, indicate the environmental impact per unit of the stressor. At the endpoint level, those factors correspond to three protection domains, i.e., human health, ecosystem quality, and resource scarcity. Recipe2016, developed by Goedkoop et al. (Goedkoop et al., 2009), provides characterization factors representative of the global scale while maintaining the possibility for several impact categories to implement characterization factors at a country and continental scale. The factors are expanded into the number of environmental interventions and added the impact of water use on human health, water use and climate change on freshwater ecosystems, and the impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways (Huijbregts et al., 2017).

$$\mathbf{HH = CF_{HH} * Emission} \tag{4}$$

$$\mathbf{DC_{HH} = MWF_{HH} * HH} \tag{5}$$

HH stands for Human Health (DALY), and CF_{HH} stands for Characterization Factor Human Health (DALY/kg CO_2 eq), as found in Table 8. DC_{HH} stands for Damage Cost Human Health (USD/year), and MWF_{HH} stands for Monetary Weight Factor Human Health (USD/DALY), which can be found in Table 9.

$$\boldsymbol{TE = CF_{TE} * Emission} \tag{6}$$

$$\mathbf{DC_{TE} = MWF_{TE} * TE} \tag{7}$$

TE stands for Terrestrial Ecosystem (species.year), and CF_{TE} stands for Characterization Factor Terrestrial Ecosystem (species.year/kg CO_2 eq), as found in Table 8. DC_{TE} stands for Damage Cost Terrestrial Ecosystem (USD/year), and MWF_{TE} stands for Monetary Weight Factor Terrestrial Ecosystem (USD/species.year), which can be found in Table 9.

$$\mathbf{AE = CF_{AE} * Emission} \tag{8}$$

$$\mathbf{DC_{AE} = MWF_{AE} * AE} \tag{9}$$

AE stands for Aquatic Ecosystem (species.year), and CF_{AE} stands for Characterization Factor Aquatic Ecosystem (species.year/kg CO_2 eq), as found in Table 8. DC_{AE} stands for Damage Cost Aquatic Ecosystem (USD/year), and MWF_{AE} stands for Monetary Weight Factor Aquatic Ecosystem (USD/species.year), which can be found in Table 9. A different approach was used to analyze damage costs related to the scarcity of crude oil resources. Gasoline, the fuel for the PHEV, is the result of the crude oil refinery. The gasoline fuel per crude oil ratio is 0.43 (Ibrahim et al., 2020), and the unit conversion from volumetric to mass.

$$\mathbf{M_{CO} = FO_{Vol} * \rho_{FO}/0.43} \tag{10}$$

$$\mathbf{DC_{OR} = CF_{OR} * M_{CO}} \tag{11}$$

M_{FO} stands for Mass of crude oil (kg), and FO_{vol} stands for Volumetric of Gasoline Fuel Oil (liter), ρ_{FO} stands for gasoline fuel oil density (kg/liter). $\boldsymbol{DC_{OR}}$ stands for damage cost for crude oil production (USD) and $\boldsymbol{CF_{OR}}$ stands for characteristic factor crude oil resources (USD/kg) as found in Table 8. Again, a different approach was used to analyze the damage cost related to the scarcity of hard coal resources. Hard Coal is the fuel for most Java Bali Fossil Power Plants.. The conversion number for the tonnage of Hard Coal into energy generated to be consumed by EV charging activity (kWh) is 8.141 kWh/kg (Euronuclear, n.d.).

$$M_{HC} = {}^{BattCap}/_{8.141} \tag{12}$$

$$DC_{CR} = CF_{CR} * M_{HC} \tag{13}$$

M_{HC} stands for Mass of hard coal (kg). $\boldsymbol{DC_{CR}}$ stands for damage cost from hard coal production (USD) and $\boldsymbol{CF_{CR}}$ stands for characteristic factor hard coal resources (USD/kg) as found in Table 8.

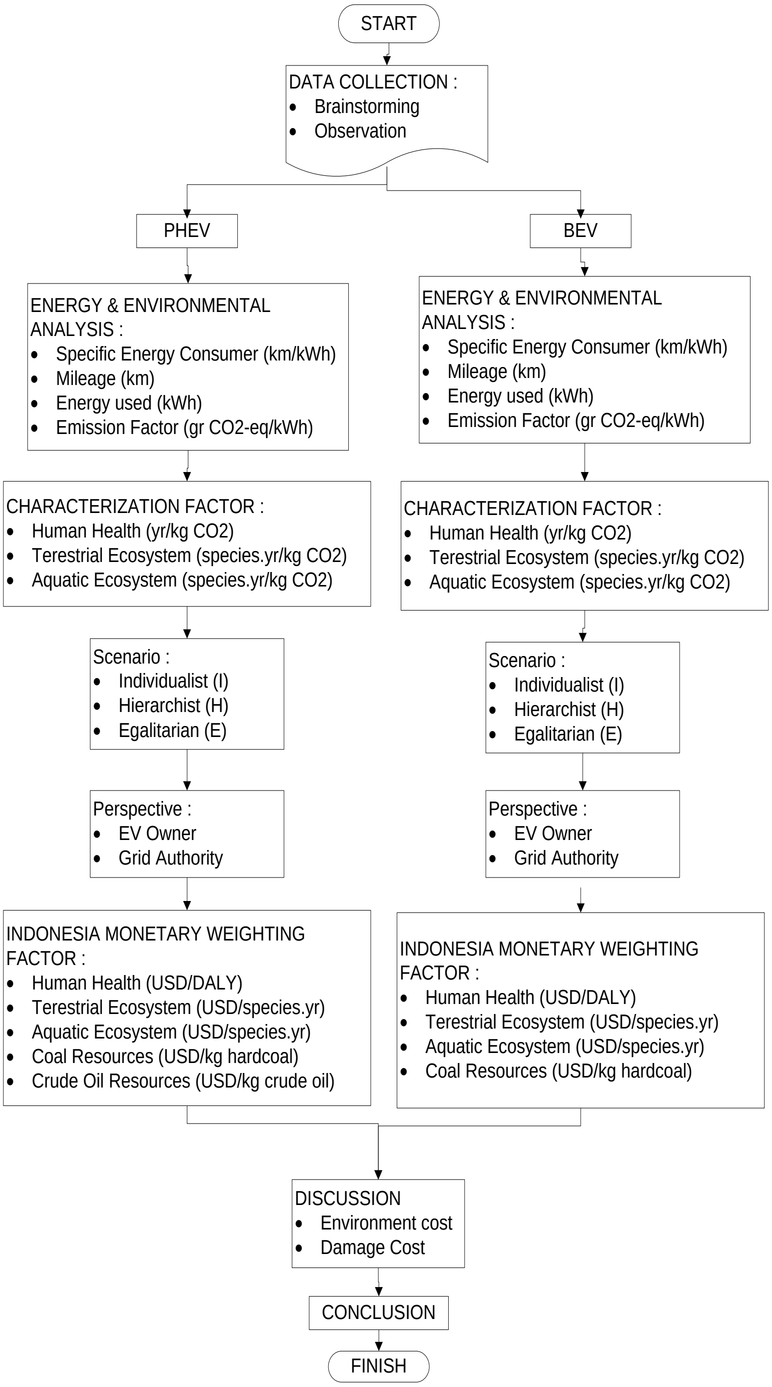

Figure 4 Research Flowchart

Emission Factor (EF) is a representative value that relates the quantity of a pollutant released into the atmosphere from an activity related to the source of the pollutant. The source of electricity generation significantly impacts EVs' LCA climate performance and varies widely between countries and regions depending on electricity mixes. We calculated CO_2 emissions using electrical energy based on the amount of electricity consumption (kWh) from coal fuel to generate electricity in the Java-Bali system, referring to Table 3.

Table 3 Indonesia CO_2 Emission Factor, Adapted (directorate general of electricity, 2019; kencono, 2015)

Component Parameter	Unit	Value
Electricity Java-Bali year 2019	gr/kWh	840
Pertamax year 2014 (Ron 95)	gr/kWh	5338.87

We calculated EF for electrical transmission, distribution, and charging of EV batteries, referring Table 4.

Table 4 World CO_2 Emission Factor, Adapted (Pipitone et al., 2021)

Component Parameter	Unit	Value
Europe's Average Power Plant	gr/kWh	299.4
World average Power Plant	gr/kWh	517.8

The emission factor for power plants in Europe is 299.4 g/kWh while the world average is 517.8 g/kWh, showing that Europe has used much clean energy with minimal CO_2 emissions. Also shown in Table 3, the difference in the emission factor between the Java-Bali network is 840 g/kWh with the world average and T&D of 556 g/kWh in Table 4, showing that most of the world has used clean energy sources, but the generators in Java-Bali still dominated by coal. Based on Nugroho et al., on the Java-Bali network, the CO_2 emission factor has reached 1060 gr/kWh (Nugroho et al., 2022).

Environmental costs are incurred during activities conducted to avoid the generation of waste that could cause damage to the environment, such as product recycling, waste elimination, and environmental research. The global warming impact, as found in Table 5, is considered the global environmental cost weighting factor.

Table 5 Environmental Cost Weighting Factor (EcoChain, 2021)

Component Parameter	Unit	Value
Global Warming Impact	USD/kg CO_2-eq/year	0.053

Environmental impact from the economic system can be viewed from two contradictory perspectives: production and consumption (Wiedmann & Lenzen, 2018), where the EV owner sided in consumption and the grid authority sided in production. Pirmana et al. (Pirmana et al., 2021) stated that Indonesia has bio-deficit conditions,ith an ecological footprint exceeding its bio-capacity. While Indonesia's bio-diversity decreases over time, the ecological footprint, i.e.,

CO_2 emission, increases. Today, Indonesia is one of the top 10 countries with the highest ecological footprint in the world (Pata et al., 2021).

Researchers chose climate change as the characterisation factor category, related to the data on the availability of CO_2 emission factors. See Tables 3, 4, and 5 and their time frames within a year. The emission of a CO_2 gas (kg) will lead to an increased atmospheric concentration of GHG (ppb), which will increase the radiative forcing capacity (w/m^2), leading to an increase in the global mean temperature (deg C). Increased temperature ultimately results in damage to human health and ecosystems. Human health is a risk that will reduce human health because of disease, natural disasters, or accidents (DALY – disability-adjusted life years). The summary of endpoint categories can be found in Table 6:

Table 6 Characterisation Endpoints Paramter (Huijbregts et al., 2017)

Characterization Parameter	Endpoint	Unit
Human Health	Damage to Human Health	DALY
Terrestrial Ecosystem	Damage to the terrestrial Ecosystem	Species.year
Aquatic Ecosystem	Damage to Aquatic Ecosystem	Species.year
Crude Oil Resources Scarcity	Damage to Crude Oil resources availability	USD (surplus cost)
Hard Coal Resources Scarcity	Damage to Hard Coal resources availability	USD (surplus cost)

Energy resource scarcity, assessed from a socio-economic perspective, reflects how economic, environmental and social factors could limit the amount of energy resources exploited (Arvidsson et al., 2021) The characterisation factor for energy resources, divided into crude oil and hard coal, is calculated from energy resources' production cost times cumulative cost-tonnage curve of fossil resources extracted divided by future production of the fossil resources (Huijbregts et al., 2017). Surplus cost for the Resources scarcity is defined as the economic burden that current resources extraction puts on future situations (Ponsioen et al., 2014).

The characterisation factors resulted from different sources of uncertainty and grouped into three scenarios to make up additional assumptions and choices for further analysis (Huijbregts et al., 2017):

1. The individualist is based on short-term interests, undisputed impact types, and technological optimism concerning human adaptation. It spans 20 years.
2. The hierarchist is based on a scientific consensus regarding the impact mechanism's time frame and plausibility. It spans 100 years.
3. The egalitarian is the most prudent, considering the most prolonged time frame and all impact pathways for which data is available. It covers a 1000-year period.

Table 7 Characterisation Factor (Huijbregts et al., 2017)

Characterization Parameter	Unit	Individualist	Hierarchist	Egalitarian
Human Health	DALY/kg CO_2-eq	8.12E-08	9.28E-7	1.25E-5
Terrestrial Ecosystem	Species. year/kg CO_2-eq	5.32E-10	2.8E-9	2.5E-8
Aquatic Ecosystem	Species. year/kg CO_2-eq	1.45E-14	7.65E-14	6.82E-13
Crude Oil Resources	USD/kg	0.457	0.457	0.457
Hard Coal Resources	USD/kg	0.034	0.034	0.034

The ecosystem quality represents the loss of local living species integrated over time due to the EV charging technology. Ecosystem living species were lost because of the higher emission, water temperature, and the lower volume of clean water in the reservoir. The fossil (crude oil and hard coal) resource scarcity represents the extra cost involved in future fossil resource extraction. The monetary weighting factor (MWF) specific to Indonesia, as shown in Table 8, is caused by human activities, in this case, transportation technology, which will transition from using oil fuel to electricity. Indonesians experience many health problems because of environmental issues, such as air pollution.

Table 8 Indonesia's Monetary Wieghting Factor (Murakami et al., 2018)

Component Parameter	Unit	Value
Human Health	USD/DALY	2.50E+04
Ecosystem	USD/Species.year	5.3E+09

Result and Discussion

Fig. 5 shows a majority of EV sampling, calculated from Fig. 2 and Fig.3, concerning the SEC and following (1), whereas the fuel is a combination of gasoline and electric fuel in PHEVs. However, BEVs still use battery electricity as their energy source. The greater the SEC, the better, which indicates that B1 has the greatest SEC, which has been caused by lesser Battery capacity. In addition, the competitive ownership price shows that the B1 has a lot more to offer than the rest of the BEV. Energy-wise, the SEC gap is based on the battery capacity when comparing BEV and PHEV.

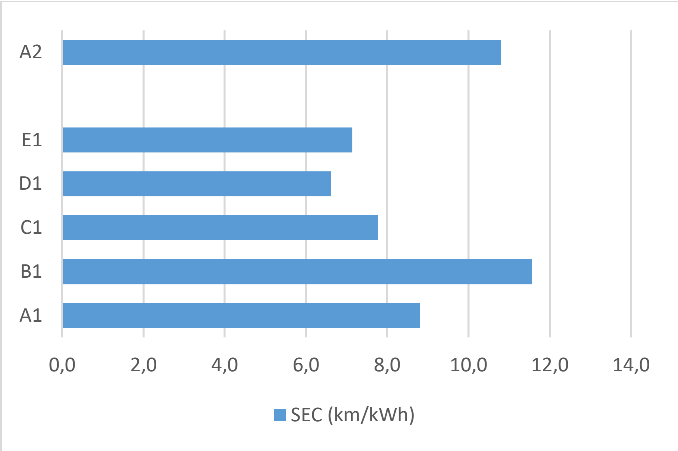

Figure 5 Research Flowchart Significant Energy User (km/kWh)

The CO2 emission from each of the categories of EV, calculated from Fig. 2 and Fig. 3, analyzed in this study are depicted in Fig. 6. With the help of (2), as shown in Fig. 6, BEVs have a CO2 emission factor advantage compared to PHEVs, and among the BEVs, the B1 has the lowest EF, which confirmed of lesser battery capacity.

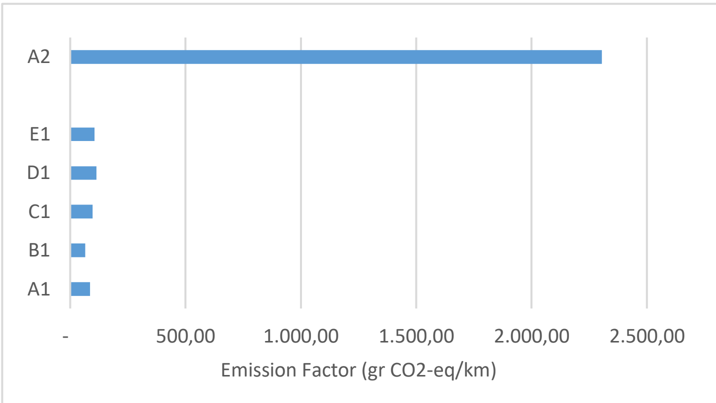

Figure 6 Emission Factor (gr CO_2-eq/km)

This study (Sang & Bekhet, 2015) also stated that environmental concern is one of the dominant factors influencing potential EV owner awareness. Aside from positive concerns toward EV ownership, the adverse concerns are related to inadequate charging facilities. DALYs (disability-adjusted life years), represent the years that are lost or that a person is disabled because of a disease such as malnutrition, malaria or diarrhea, which can be categorized as human health disturbance or an accident such as flood risk because of the temperature increase (Huijbregts et al., 2017). Using table 6 and (4) there are 3 different scenarios for each BEV and PHEV.

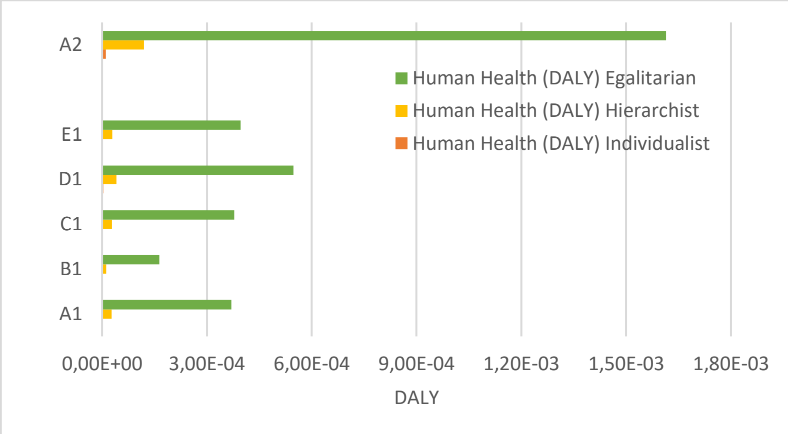

Figure 7 Human Health (DALY)

As found in Fig. 7, both for the EV owner and the community, their health risk is lower for having BEVs instead of PHEV, due to: (1) As BEVs do not require gasoline or diesel fuel, they eliminate the exposure to harmful chemicals such as benzene, formaldehyde, and acetaldehyde from fuel combustion, which have negative health effects; (2) BEVs produce zero tailpipe emissions and local air quality is significantly improved in areas where BEVs are more prevalent, reducing levels of harmful pollutants such as NOx, PM2.5, and volatile organic compounds (VOCs); (3) BEVs offer a lower carbon footprint when powered by renewable energy (e.g., solar, wind, or hydroelectric power). The health risks associated with climate change including heat-related illnesses, vector-borne diseases, and mental health impacts because of extreme weather can be mitigated by reducing emissions from transportation. While among the BEV, B1 has the least DALY, and the Individualist has the smallest number compared to Hierarchist and Egalitarian, which is calculated from the Table 7, that the Individualist characteristics scenario has the lowest number.

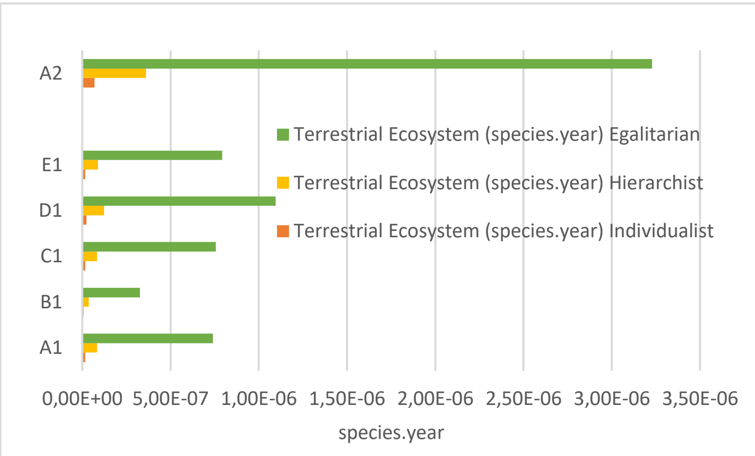

Figure 8 Terrestrial Ecosystem (species. year)

Damage to the terrestrial ecosystem is because of the temperature increase primarily driven by climate change relates to greenhouse gas emissions and local air pollution generated by their use, which might cause species to disappear above the ground in a year. Using table 6 and (6) there are 3 different scenarios for each BEV and PHEV. As found in Fig. 8, for both EV owners, the terrestrial ecosystem damage is lower for having BEV instead of PHEV. While BEVs themselves do not emit greenhouse gases, the carbon intensity of the electricity used to charge them plays a significant role. If the electricity comes from renewable sources like solar, wind, or hydropower, BEVs have a minimal impact on greenhouse gas emissions. However, if the grid relies on fossil fuels (e.g., coal, natural gas), their indirect emissions can contribute to temperature increase and global warming. Their contribution to temperature rises largely depends on how clean the electricity used for charging is. As the energy grid shifts toward renewables, the overall environmental impact of BEVs on global warming and terrestrial ecosystems continues to decrease. While among the BEV, B1 has the most minor species.year, and the Individualist has the smallest number compared to Hierarchist and Egalitarian. which is calculated from the Table 7, that the Individualist characteristics scenario has the lowest number.

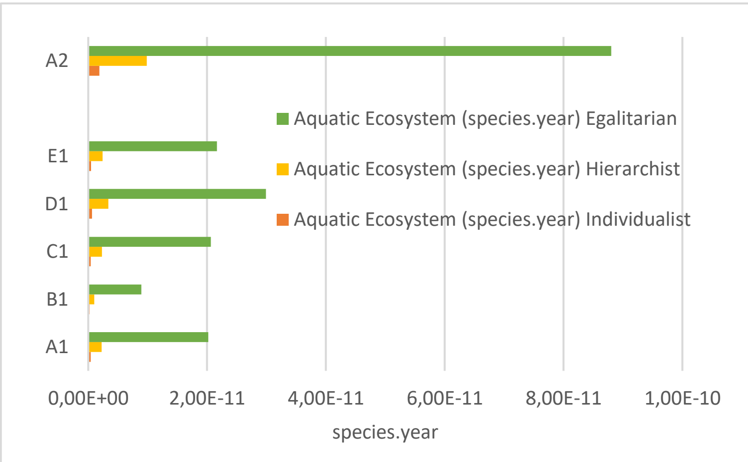

Figure 9. Aquatic Ecosystem (species. year)

Damage to the aquatic ecosystem is because of temperature changes and the river basin's total water volume, is a significant concern, as rising temperatures because of climate change can have severe consequences for aquatic life. This damage is influenced by the greenhouse gas emissions from various sources, including vehicles, which might cause species to disappear within a year. Increased temperatures, especially in freshwater ecosystems, can cause thermal pollution, which occurs when hot water (often from industrial processes or energy production) is released into natural water bodies. This can disrupt aquatic life, making it difficult for species to survive or reproduce. The influence of global temperature increase in river discharge and subsequence expected changes in fish species occurrences. As temperatures rise, oxygen

levels decrease, making it harder for many species to survive. As the electric grid becomes more renewable, this impact will continue to decline. Using table 6 and (8) there are 3 different scenarios for each BEV and PHEV. As found in Fig. 9, the EV owner's aquatic ecosystem damage is lower for having BEV instead of PHEV. While among the BEV, B1 has the minor species.year, the individualist group has the smallest number compared to the hierarchist and egalitarian groups. All the characterization factors show that the Egalitarian scenarios have the highest health impact for HH and disappearing species for TE and AE, since is been accumulated in the timeframe of 1000 years, instead of Individualist. For the individualist, all the parameters are calculated in the timeframe of 20 years, while the hierarchist is calculated in the timeframe of 100 years.
The damage cost is determined using a human (health) approach, ecosystem (on the surface-terrestrial and clean fresh water - aquatic), and the scarcity of fossil resources. Damage Cost, as one of the public interests, is a cost that has the potential to occur because of damage, which is calculated using a weighting factor. See Table 8, along with a characteristic factor, which refers to Table 7. Total unit damage cost is the potential damage cost arising from the use of EVs, both from Human Health (HH), Terrestrial Ecosystem (TE), Aquatic Ecosystem (AE), Crude Oil Resources Exploitation (COE), and Hard Coal Resources Exploitation (HCE). For the parameters HH, TE, and AE, the characterisation factor is based on Table 6, with the multiplier unit being CO2 equivalent weight units, with (5) for HH, (7) for TE and (9) for AE. Meanwhile, the COE and HCE parameters use the assumption of primary energy consumption to produce final kWh of electricity with (10) for COE and (11) for HCE. When considering the damage costs caused by the use of Electric Vehicles (EVs), both from the perspective of the EV owner and the grid owner, it's important to consider several factors. These include carbon emissions, energy consumption, externalities (such as damage to ecosystems and human health), and the potential for economic benefits from transitioning to cleaner energy sources. Below, we'll explore both perspectives to understand the cost of damage associated with electric vehicles and the energy grid.

EV Owner Perspective

EV owners expect to benefit from noiseless, vibration-free, and instant power, and in terms of rupiah, the energy consumption is lower than that of conventional cars. Also, participating in the energy transition since energy consumption and carbon emissions' impact were relatively lower than fuel-based vehicles. One liter of gasoline (Ron 95) has emissions of 2.22 kg CO2-eq, while 1 kWh from a Jawa Bali Power Grid has 0.84 kg CO2-eq (Directorate General of Electricity, 2019). While the mileage distance varies, depending on the specification of the motor or engine, the gap reduction is over 60 %; one can say that Electrification in land transport, especially in light-duty vehicles, the environment can benefit from the massive CO2 emission reduction. In the past, the emissions were on the roads; shortly, emissions only come from fossil power plants.

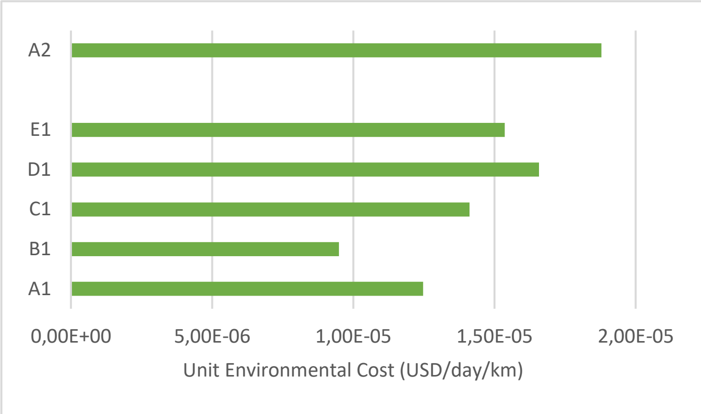

Figure 10 Unit Environmental Cost (USD/day/km)

Using Table 5 and (3), the result can be found in Fig. 10.. From Fig. 7, the PHEV (A2) has a gap compared to the BEV since the PHEV still uses gasoline as the fuel. B1 has the lowest environmental cost (USD/day/km) because of the highest SEC (km/kWh). D1 has the highest environmental cost (USD/day/km) and has a slight gap from A2 since D1 has the lowest SEC (km/kWh).

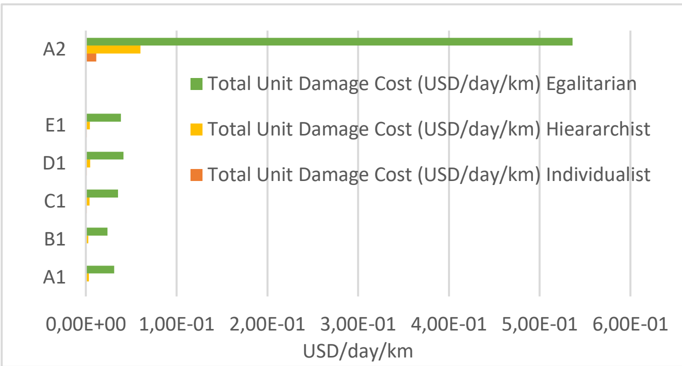

Figure 11 Total Unit Damage Cost (USD/day/km)

The total Unit Damage cost found in Fig. 11, on A2 is far greater than the BEV because A2 is powered by both Internal Combustion Engine (ICE) and Electric Motor (EM), where the mileage distance using EM is only 5%, and when the battery runs dry, the ICE takes over. The damage cost is estimated from the amount of CO2 emitted from gasoline engines and power drawn from fossil power plants in the grid. From the BEV, the CO2 emission is estimated from the power drawn from fossil power plants to recharge the battery. The greater the battery capacity and EM specification, the more excellent the mileage related to SEC can be found in Fig. 5.

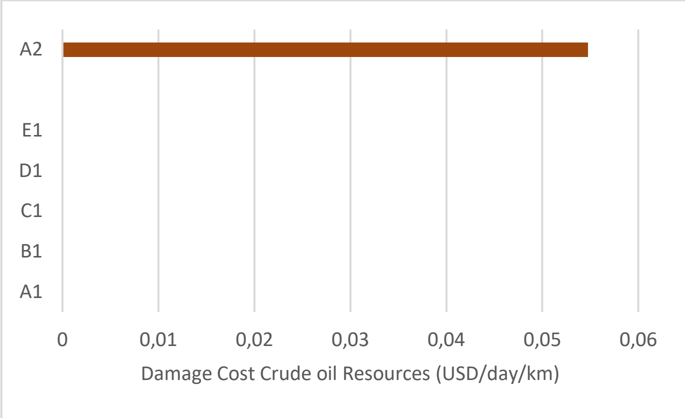

Figure 12 Damage Cost Crude Oil Resources (USD/day/km)

As Table 6 indicates, individualist, hierarchist, and egalitarian scenarios show no difference in crude oil resource scarcity. The scarcity reflected the number of monetary weighting factors for crude oil resource depletion in the future, which leads to increased demand for energy for extraction or exploitation. The cost of damage to crude oil resources is shown in Fig. 12, for the A2 is inevitable, which PHEV owners should realize.

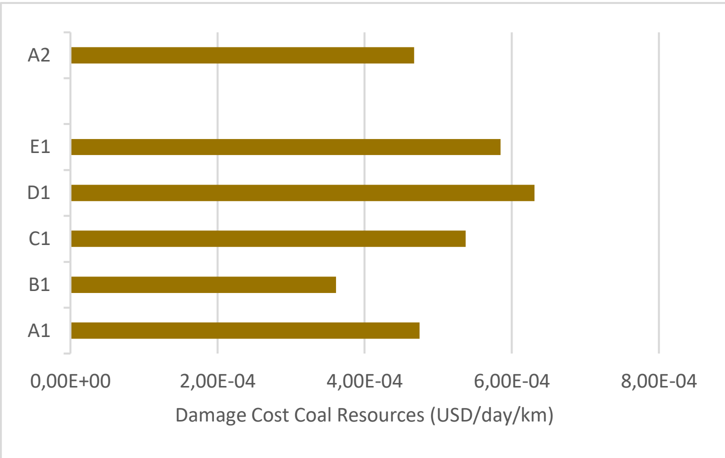

Figure 13 Damage Cost Hard Coal Resources (USD/day/km)

As shown in table 6, the three (3) previously stated scenarios show no difference in hard coal resource scarcity. The scarcity reflected the number of monetary weighting factors for the depletion of hard coal resources in the future, which leads to increased energy demand for extraction or exploitation, which is lower than crude oil at around 7.44%. The damage cost of hard coal resources, found in Fig. 13, for the A2 is lower than most of the BEVs since the battery capacity of the PHEV is smaller than that of the BEV.

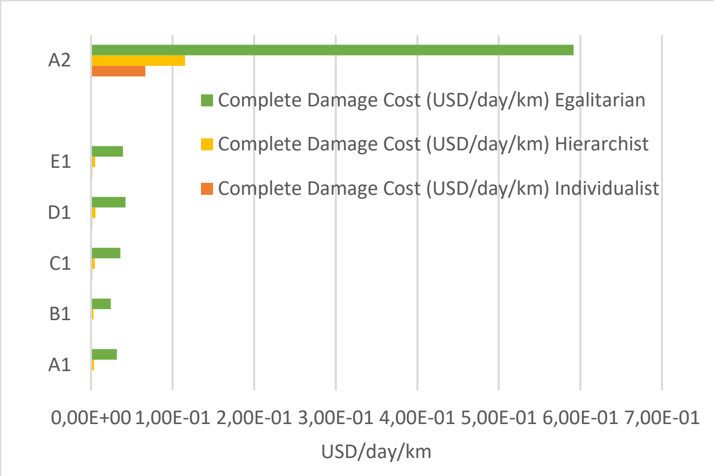

Figure 14 Total Damage Cost (USD/day/km)

The complete damage cost of EV charging from the EV owner's perspective is the total damage cost caused by HH, TE and AE, combined with energy resources scarcity, both CRE and HCE for PHEV and HCE for BEV, which has resulted in a significant value of PHEV, all for three different scenarios, compared to the BEV. Potential EV owners who would like to bear fewer consequences to the environment and potentially less damage cost to the electricity bill should choose the BEV, but with the consequences of worrying because of insufficient EVCS nearby and significantly few EVCS that could provide ultra-fast charging methods, as compared to the regional gasoline station, which could refill the fuel within minutes. Comparing the amount of environmental cost and the complete damage cost for PHEV, found in Fig. 14,, where environmental cost is only 0.03% than damage cost. For BEV, the environmental cost is only around 1.1% of the damage cost.

Grid Authority Perspective

In Indonesia, the electricity tariff charged to EV owners when charging the battery at Public Electric Vehicle Charging Stations (EVCS) is higher than the residential electricity tariff. In residential areas, based on Minister of Energy and Mineral Resources Regulation no. 8 in 2023, depending on the customer group, between Rp. 1,352.00 / kWh for the 900VA power group, Rp. 1,444.70 / kWh for the 1300-2200VA power group and Rp. 1,699.53 / kWh for the 3500-6600 VA power group. Meanwhile, based on Minister of Energy and Mineral Resources Regulation no. 1 of 2023, the charging rate at EVCS is set at IDR. 2,444.00 / kWh. These rates apply to many charging technology, namely slow charging, medium charging, fast charging, and ultrafast charging.

However, for fast charging and ultrafast charging technology, the government provides an additional maximum service fee, namely IDR 25,000 per charge for EVCS fast charging (25 kW to 50 kW) and IDR 57,000 per charge for EVCS ultrafast charging (>50 kW). This service fee is charged because the investment required to provide fast charging facilities exceeds slow or regular charging. Apart from that, fast charging also benefits electric car users because it can save time. With the existing costs, charging an electric car can be more economical. As the population of EVCS continues to expand, the BEV owners will eventually have more easy-to-find locations and convenient access for EV charging. This availability can reduce cost and enhance the flexibility of BEVs owner, compared to the PHEV, which may have a more frequent time for gasoline refueling. The broader number of EVCS can enhance the overall cost-effectiveness compared to PHEV, by having the fuel gas station.

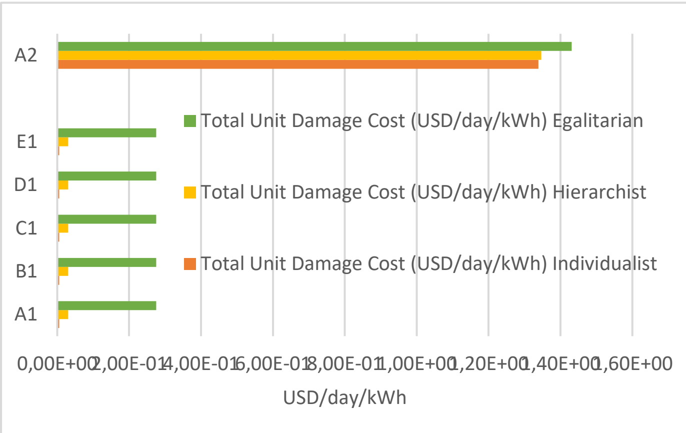

Figure 15 Total Unit Damage Cost (USD/day/kWh)

As found from the EV owner's perspective, the total unit damage cost in Fig. 15, of A2 is far greater than BEV because A2 is powered by both ICE and EM. As found in the BEV, the unit damage cost is the same for all kinds of BEVs since, from the Grid Authority Perspective, we use energy units as the main parameter for consideration, although each BEV has different technical specifications.

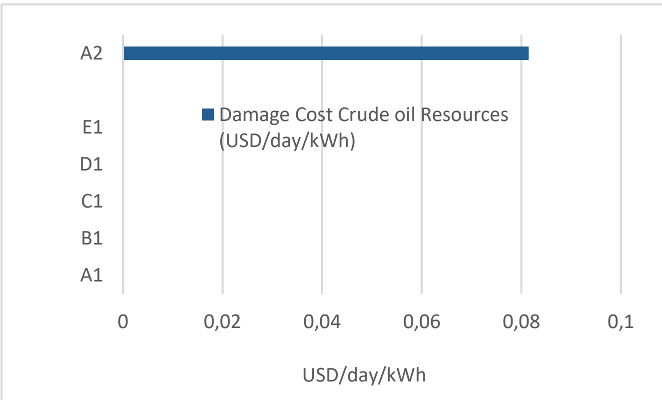

Figure 16 Damage Cost Crude Oil Resources (USD/day/kWh)

The damage cost of crude oil resources, found in Fig. 16, for the A2 is inevitable, which PHEV owners should realize.

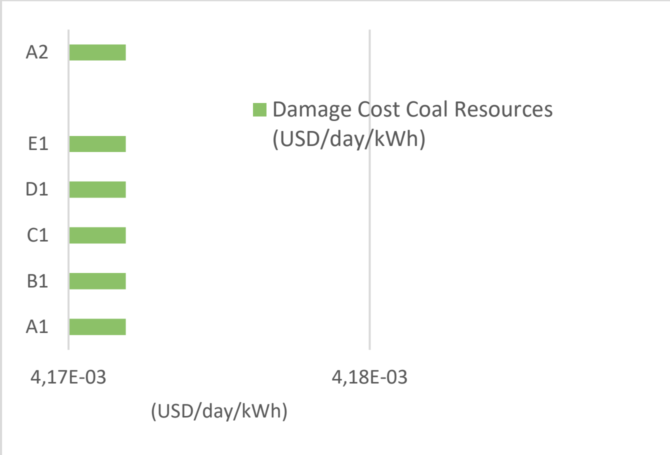

Figure 17 Damage Cost Hard Coal Resources (USD/day/kWh)

The damage cost of hard coal resources, found in Fig. 17, for all the BEV and PHEV, is seen as equal; although all the EVs have different specifications regarding energy consumption, they have the exact damage cost.

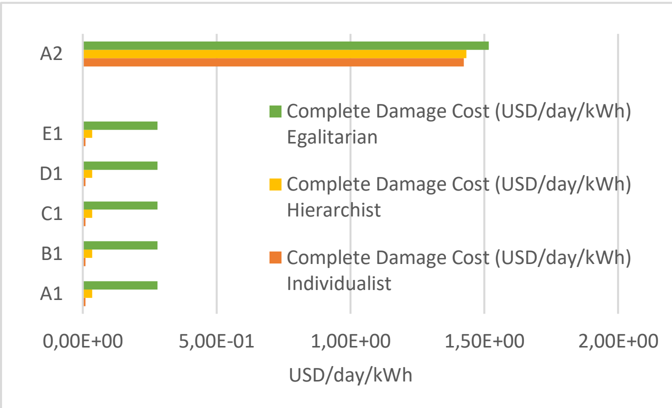

Figure 18 Complete Damage Cost (USD/day/kWh)

Comparing the amount of environmental cost and the complete damage cost for PHEV, found in Fig. 18, where environmental cost is only 0.13% than damage cost. For BEV, the environmental cost is only around 1.1% of the damage cost. Environmental costs focus specifically on ecological impacts, while complete damage costs encompass a broader range of economic and social consequences. With the existing costs, charging a BEV can be more economical than a PHEV. The reason is that a BEV with 1 kWh of power can cover a mileage of 6.6 up to 11.6 km. Meanwhile, 1 liter of gasoline can cover a mileage of around 16.6 km, meaning that 1 liter equals 8.9 kWh, that may be used in the city driving scenarios, where EV mode may not be used extensively. Nevertheless, the average efficiency of a gasoline engine is 15%, so 1 liter of gasoline is equivalent to 1.335 kWh. If the price of electricity at EVCS is IDR 2,444.00 per kWh, then an electric car only needs IDR 3,263.00 per equivalent liter. Consumers need to pay only IDR 3,263 for 1.335 kWh of electricity to travel 6.6 to 11.6 km. Moreover, it could be cheaper if the EV charged the battery at their residence, which costs them Rp. 2,268.87. Aside from the charging perspective, the BEV has fewer moving parts than PHEVs, which leads to a lesser maintenance cost. Compared to the EM, there are no oil changes or excess thermal to deal with in the complex ICE. While PHEVs offer the flexibility of a gasoline backup, this feature often leads to reliance on fossil fuels, potentially impacting national fuel costs. In contrast, BEVs minimize gasoline use, making daily driving needs forecasting essential to reduce range anxiety due to their larger batteries.

The EV will play a vital role in the energy transition mechanism, and having different charging strategies can adapt to the flexibility of EV charging tariffs. Modifying the Indonesia regional EV charging tariff into Real-time Elasticity has been considered, to promote the faster penetration of EV utilization (Sesotyo et al., 2024b). Understanding the cost structure is vital for determining the decision maker. Effective policies and decisions often aim to minimize environmental costs while considering the significant implications of complete damage costs. However, the environmental damage of EV use depends also on the residential electricity prices. Nehiba found that 10% of the price increment resulted in 1 % mileage reduction (Nehiba, 2024). While Nazir and Wong has found the relation of damage cost of EV usage to the purchase price and fuel cost of the power generation. It is said that the damage cost of EV is greater than its energy cost (Nazir & Wong, 2012). Petrauskiene et al., has made a study of the environmental cost of EV charging considering the energy mix for the grid supply and its time of use for charging. From late evening to 7 a.m. morning will be the best option for battery charging (Petrauskienė et al., 2021). Regarding EVs, batteries are a critical technology that will determine the adoption of EVs as the replacement for conventional ICE and vehicle autonomy. With the proper battery management system, the battery life time could last 4,400 charge/discharge cycles, or in other words, approximately 12 years with required daily charging (Raustad & Dunn, 2017).

Aside from the above values, quantifying environmental costs is complex because of the uncertain values of ecosystems and services not recognised in the community. The complexity of uncertain values may lead to inaccurate environmental and damage costs data. In contrast, limited or challenging efforts to obtain the data may cause a shorter cost forecast. Overall, charging a BEV is more economical compared to a PHEV. Parameters for the charging the EVs car, like lesser operating cost, greater energy efficiency, fewer maintenance needs, and the proposed and already implemented some financial incentives, are to keep evolving, the benefits of BEVs are likely to become even more uttered.

Conclusions

Beyond the cost of electricity generation, transmission and distribution, tax, incentive and surcharge, DC must be revealed for all stakeholders' awareness. This paper has an environmental cost for any energy related to CO2 emission, but damage cost offers more comprehensive coverage for mitigating the risk of EV charging activity, considering the raw extraction for battery material. The potential cost to compensate for DALY of human health and the disappearing of terrestrial and aquatic species in a year and mitigating the scarcity of energy resources, as a practical implication, has to be addressed in the tariff issued to the EV owners and implied in the Grid Authority tariff formulation. PHEV utilization caused more significant DC than BEV in term of emission, but BEV utilization cause more significant DC than PHEV in terms of raw extraction for battery material. The total DC for a 20 kWh BEV = 0.12 ± 0.01 USD/kWh compared to an 8 kWh PHEV = 0.08 ± 0.005 USD/kWh.

Our results show DC has to be estimated in terms of energy (/kWh). Charging by kWh creates a fair rate and is uniformly quantized for every BEV, while by km, as analyzed in the EV owner perspective, it will create uncertainty associated with EV specification. Grid authority perspective plays a vital role in the tariff strategy for the EV owner to increase the EV population, besides the charging station, in residential and public places. While the battery capacity play significant role for the DC in the raw extraction material. Therefore, there is an extra DC of 0.02 USD/kWh for BEVs and 0.015 USD/kWh for PHEVs. The limitation of the current study is considering Coal as the major source of Indonesia power generation. Future study must analyze the sensitivity of each endpoint indicators affect the robustness for acquiring the confidence interval, to evaluate how changes in factors such as electricity prices, EV adoption rates, and charging infrastructure development might impact on total costs while considering the economic impact of potential energy shortages or increased energy prices because of the increasing demand for EV charging and energy mix scenario for sustainable environment.

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