SEPTEMBER 2023

# COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS AND TWO-WHEELERS IN INDONESIA

ZAMIR MERA AND GEORG BIEKER

## ACKNOWLEDGMENTS

Funding for this work was generously provided by the Crux Alliance. The authors thank Rizqi Nugroho of Universitas Indonesia and Life Cycle Indonesia, Faris Adnan Padhilah, Rahmi Puspita Sari, and Julius Christian of IESR, and Shane McDonagh of IEA for helpful reviews; these reviews do not imply any endorsement. Thanks also to our ICCT colleagues Aditya Mahalana, Chelsea Baldino, Francisco Posada, and Tenny Kristiana for reviewing this report. Any errors are the authors' own.

Edited by Jen Callahan



International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

# EXECUTIVE SUMMARY

Limiting global warming to less than 2 °C above pre-industrial levels requires global, concerted effort to reduce greenhouse gas (GHG) emissions. Indonesia has committed to this by setting a target of reaching net-zero GHG emissions by 2060 or sooner. The transport sector is about 15% of the country's GHG emissions today, and growth in the vehicle fleet is expected in the coming years alongside economic development. Deep decarbonization of the transport sector is a key factor in reaching net-zero emissions by 2060. Importantly, measures to reduce GHG emissions from on-road transport would also bring cleaner air and associated public health benefits, and benefit the economy by reducing oil imports and public spending on fossil fuel subsidies. A shift from current gasoline and diesel internal combustion engine vehicles (ICEVs) to hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (FCEVs), and increasing the use of biofuels, are among the measures being discussed in Indonesia to reduce transport emissions.

This report begins with a life-cycle assessment (LCA) that compares the GHG emissions of passenger cars and two-wheelers of different power trains. It analyzes emissions from fuel combustion in vehicles, fuel and electricity production, maintenance, and vehicle and battery manufacturing. Based on representative vehicle models for scooters, A segment cars, sport utility vehicles (SUVs), and multi-purpose vehicles (MPVs), it compares life-cycle GHG emissions of gasoline ICEVs and BEVs, and, where possible, diesel ICEVs, HEVs, PHEVs, and hydrogen FCEVs. In addition to comparing GHG emissions over the lifetime of vehicles sold in 2023, the study estimates emissions over the lifetime of vehicles sold in 2030. Based on the results, the report explores possible policy options for Indonesia.

Key results include the following:

**Battery electric vehicles have the lowest life-cycle GHG emissions already today and approach zero emissions in the future.** As displayed in Figure ES.1, battery electric SUVs and electric scooters sold today have 47%–54% and 26%–35% lower emissions, respectively, than their gasoline equivalents. The range of values corresponds to the development of the electricity mix during the lifetime of the vehicles according to a Baseline scenario (higher emissions) and a scenario in line with the Government of Indonesia's target of reaching net-zero emissions by 2060 (lower emissions; the "Net-zero 2060" scenario). For vehicles sold in 2030, the life-cycle emissions of battery electric SUVs and electric scooters are estimated to be 52%–65% and 34%–51% lower than for today's gasoline vehicles. Once fully powered by renewable electricity, they would have 85%–89% lower emissions than gasoline vehicles. Similar values are found for A segment cars and MPVs.

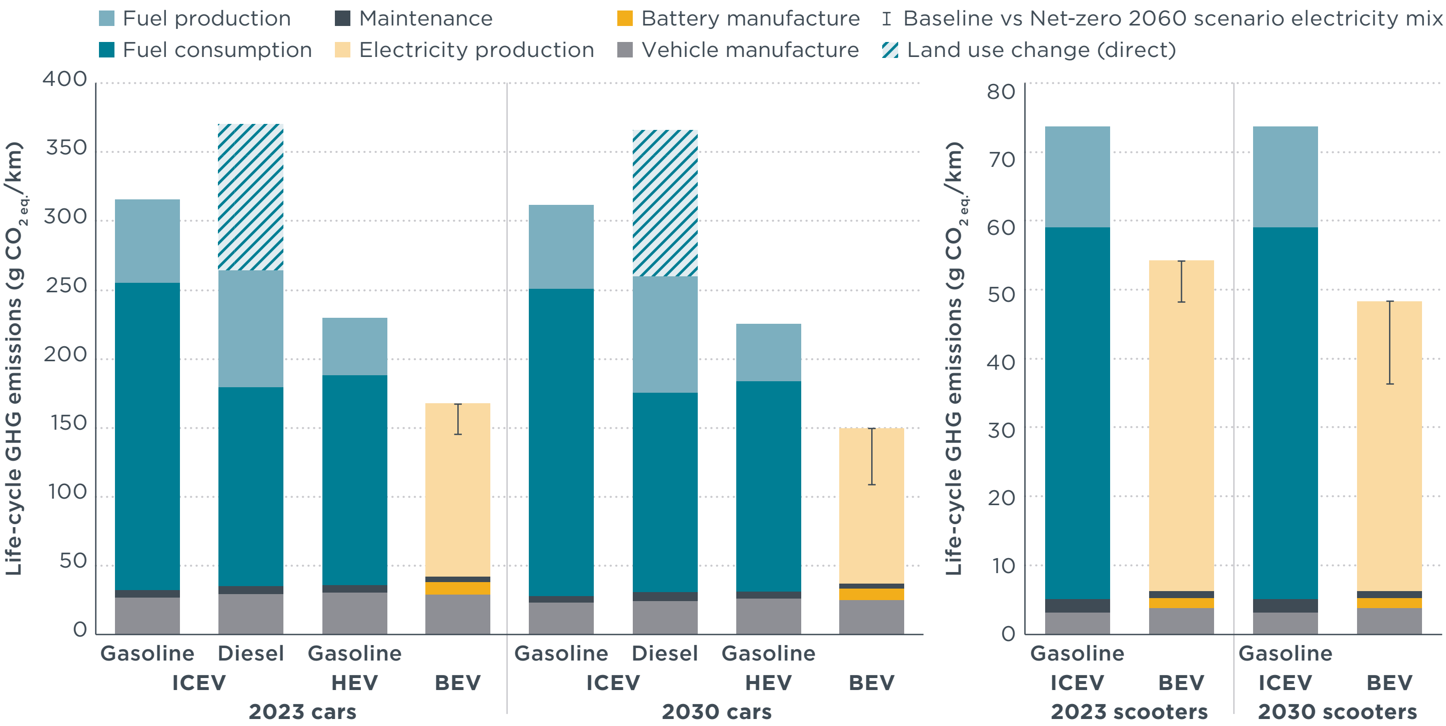



**Figure ES.1.** Life-cycle GHG emissions of SUV segment gasoline and diesel internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), and battery electric vehicles (BEVs), as well as gasoline and electric scooters sold in Indonesia in 2023 and projected to be sold in 2030. The error bars indicate the differences between the development of the electricity mix according to a current policy Baseline scenario (higher values) and a development in line with the Government of Indonesia's target of reaching net-zero emissions by 2060.

**The GHG emissions of diesel cars are more than twice that of battery electric cars.** When including land use change emissions, which correspond to the emissions caused by converting natural areas to agricultural use for biodiesel production, SUVs powered with the current 35% biodiesel blend (B35) have twice the emissions of comparable battery electric models. Even when compared with gasoline vehicles, estimated life-cycle GHG emissions for diesel ICEVs are 17% higher.

**Hybrids and plug-in hybrids have higher life-cycle GHG emissions than BEVs.** HEVs consume less fuel than conventional gasoline cars; for 2023 cars in the SUV segment, they offer a 27% reduction in life-cycle GHG emissions compared with conventional gasoline cars. This GHG emission benefit is at the upper end compared to what is found in Europe. Still, it is only about half as high as found for battery electric cars in the same segment. The GHG emission benefit of PHEVs depends on how much they are driven on electricity or fossil fuel. When considering average real-world use, the emissions of PHEVs can be almost as high as for conventional gasoline vehicles. Given that the electricity mix is expected to decarbonize over time, the GHG emission benefit continuously increases for future BEVs, while HEVs and PHEVs remain largely dependent on the combustion of fossil fuels. Thus, unlike BEVs, hybrids do not offer a reduction in GHG emissions that can approach zero emissions for Indonesia's vehicle fleet.

**The climate performance of FCEVs varies significantly under different hydrogen production pathways.** For natural gas-based hydrogen, the life-cycle GHG emissions of driving an FCEV today are estimated to be 28% lower than for a comparable gasoline vehicle, while driving with coal-based hydrogen has 10% higher emissions. With electricity-based hydrogen produced from the average electricity mix, GHG emissions are as much as 75% higher than for gasoline cars. However, when using only renewable electricity to produce hydrogen the emissions are 75% lower emissions than gasoline ICEVs. FCEVs are thus only a low-carbon pathway if solely powered by hydrogen produced from renewable electricity.

These results present several policy options that Indonesian officials could consider:

**Specific policy supports would help spur domestic battery and electric vehicle production in Indonesia.** As Indonesia is the world's largest supplier of nickel and has rich reserves of other key battery materials including cobalt, manganese, copper, and aluminium, creating a battery and electric vehicle manufacturing industry in Indonesia provides the potential for economic growth and would create new jobs. Increasing the share of electric vehicles in the on-road fleet would also reduce oil imports and public spending on fuel subsidies. The Ministry of Industry's electric vehicle production and sales share targets combined with the tax deduction for electric vehicle manufacturers are important steps to support the development of a domestic battery and electric vehicle supply chain. However, experience in other markets shows that more government interventions are likely needed to develop the electric vehicle market.

**Phasing out sales of new combustion engine cars and two-wheelers, including hybrids and plug-in hybrids by around 2040 would help align the transport sector with Indonesia's 2060 net-zero target.** In combination with a continuously decarbonizing power sector, battery electric passenger cars and two-wheelers can approach zero emissions in the long term. In contrast, conventional gasoline and diesel ICEVs, HEVs, and PHEVs cannot approach zero emissions, as they mainly rely on the combustion of fossil fuels (and the use of biofuels does not necessarily have a large emission benefit compared to fossil fuels). As passenger cars in Indonesia have an average vehicle lifetime of 18–20 years, a transition to a fully electric fleet by 2060 requires that from around 2040, no new combustion engine cars, hybrids, or plug-in hybrids are sold in Indonesia. For electric two-wheelers, full electrification can likely be achieved earlier.

**Electric vehicle sales share mandates and/or corporate average fuel economy standards for passenger cars and two-wheelers would help manufacturers to continuously increase the share of BEVs in their fleets.** Experiences from China, the European Union, and other markets show that the increase in BEV shares is most effectively achieved by the introduction of corporate average fuel economy standards in combination with purchase subsidies and tax incentives for electric vehicles. In the short term, corporate average fuel economy standards also reduce the fuel consumption and emissions of combustion engine cars and spur a shift to more fuel-efficient vehicles. Alternatively, experiences in California and other U.S. states show that electric vehicle sales share mandates can target an increase in BEV sales more directly.

**BEV purchase subsidies and tax incentives can be balanced by higher taxes on high-polluting vehicles.** Indonesia's current purchase subsidies, value-added tax reductions, and luxury tax reductions for electric passenger cars and two-wheelers are important steps to help reduce the purchase price gap between BEVs and ICEVs. To balance public expenditures on BEV incentives, the Government could introduce a revenue-neutral feebate program that compensates for such incentives with higher taxes on high-polluting vehicles. Such feebate programs have successfully been introduced in France, Thailand, and Singapore.

# TABLE OF CONTENTS

# INTRODUCTION

Indonesia is particularly vulnerable to future increases in coastal and rain-induced flooding and the extreme drought and heat events associated with climate change (World Bank and Asian Development Bank, 2021). The country has committed to mitigation efforts under the Paris Agreement. By 2030, the Government of Indonesia's Enhanced Nationally Determined Contribution (NDC) foresees a 32% reduction of greenhouse gas (GHG) emissions compared to a business-as-usual (BAU) scenario. If Indonesia receives support from other countries, the NDC goes further and targets 43% lower emissions than the BAU scenario. The Government of Indonesia's Long-Term Low Emissions Strategy targets net-zero GHG emissions by 2060 or sooner (Government of Indonesia, 2022).

Transport is currently the source of approximately 15% of Indonesia's GHG emissions (Ge et al., 2022). About 50% of transport emissions are from road passenger transport; these emissions are evenly split between passenger cars and a large stock of two- and three-wheelers (International Energy Agency [IEA], 2022a). In 2021 alone, 5.2 million new two-wheelers entered the Indonesian fleet (Motorcycles Data, 2022). That same year, 820,000 new passenger cars were sold in Indonesia (MarkLines, 2022). With continuous economic growth, the number of vehicles in Indonesia is expected to increase in the coming decades (IEA, 2022a; International Council on Clean Transportation [ICCT], 2020). At the same time, to align with the goal of economy-wide net-zero emissions by 2060 or sooner, the GHG emissions of the Indonesian vehicle fleet will need to drop dramatically.

This study compares the potential of various power trains and fuel pathways to decarbonize the two-wheeler and passenger car vehicle fleets in Indonesia. As a life-cycle assessment (LCA), it covers the GHG emissions of fuel combustion in the vehicles, the emissions corresponding to fuel and electricity production, and the emissions from vehicle and battery manufacturing. The analysis compares gasoline internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) and, depending on the segment, also diesel ICEVs and hybrid electric vehicles (HEVs). The study further evaluates the potential GHG emissions impact of hydrogen fuel cell electric vehicles (FCEVs) in Indonesia. It is based on representative vehicle models for scooters, A segment cars, sport utility vehicles (SUVs), and multi-purpose vehicles (MPVs). We take the current average biofuel blends and electricity mix and consider developments in each over the lifetime of the vehicles sold in 2023. For future biofuel blends and electricity mix, a scenario based on the effect of current policies is compared with alternative scenarios. To estimate GHG emissions of future vehicles, the study also compares the life-cycle GHG emissions of hypothetical two-wheelers and passenger cars sold in 2030.

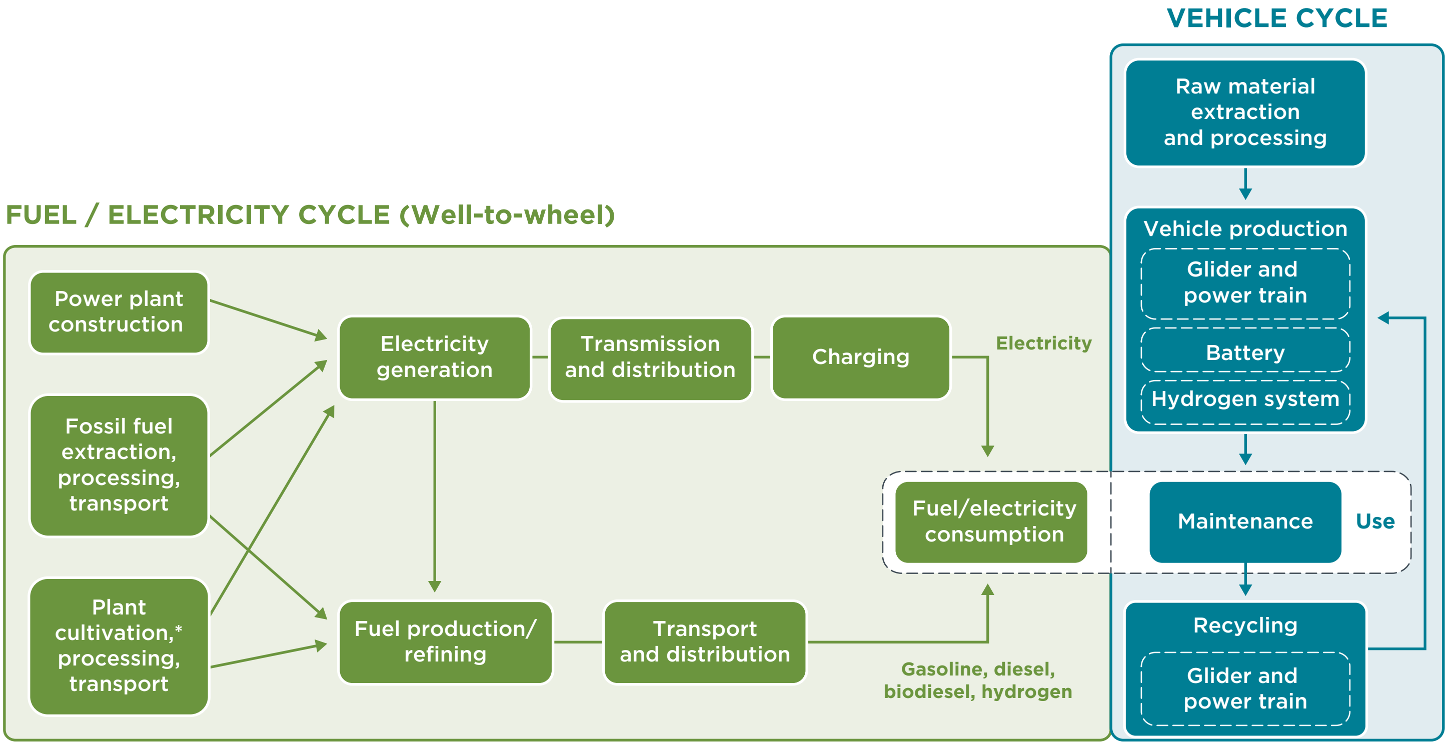
After presenting the details and results of the LCA for current and future vehicles, we provide a summary and discussion. The study closes with options Indonesian policymakers could consider based on the results and lessons from other markets.

## DATA AND METHODOLOGY

### GOAL AND SCOPE

The goal of this LCA is to identify which power trains and energy pathways offer the largest GHG emissions reduction in passenger cars and two-wheelers in Indonesia within existing and alternative policy frameworks. The functional unit is grams of carbon dioxide equivalent ($CO_{2\ eq.}$) per distance traveled during the lifetime of a vehicle (g $CO_{2\ eq.}$/km). Methane ($CH_4$) and nitrous oxide ($N_2O$) emissions are considered based on their 100-year global warming potential (Intergovernmental Panel on Climate Change [IPCC], 2021). This LCA follows an attributional approach, which means it considers the average GHG emissions attributed to a vehicle of the respective power train type and segment, and to the average fuel or electricity mix over the vehicle's lifetime.

The general scope and system boundary of this LCA are shown in Figure 1. This is based on the scope and methodology of an LCA of passenger cars in the European Union, the United States, China, and India previously published by the ICCT (Bieker, 2021a). The scope covers the GHG emissions of the vehicle cycle, which includes the production, maintenance, and recycling of the vehicles, and the fuel cycle, which includes the GHG emissions of the fuel and electricity production and consumption.




* Includes direct land use change (DLUC) emissions for biomass and biofuel production

**Figure 1.** General scope and system boundary of the LCA analysis.

For the vehicle cycle, the study covers emissions from raw material extraction and processing, component manufacturing and assembly, and vehicle recycling. For BEVs and electric two-wheelers, emissions corresponding to the battery production, which also include emissions from the extraction and processing of the raw materials, are presented separately from emissions from the production of the rest of the vehicle. Similarly, emissions corresponding to the production of hydrogen storage tanks and fuel cells are presented separately. The vehicle cycle also covers the use of consumables and the in-service replacement of vehicle parts.

**Table 1.** Scope of GHG emissions in the vehicle cycle.

| Data | Summary of scope |
|---|---|
| **Glider and powertrain** | Production of the vehicle, including raw material extraction and processing, component manufacture, vehicle assembly; recycling of vehicle components, time-sensitive hybrid of avoided burden and cut-off approach |
| **Battery** | Production of battery packs, including extracting and processing of raw materials, cell production, and pack assembly |
| **Hydrogen system** | Production of hydrogen tanks and fuel cells, including raw material extraction and processing, and component manufacture |
| **Maintenance** | In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, urea, and more |

The fuel and electricity cycle, or “well-to-wheel” (WTW), covers the GHG emissions corresponding to fossil fuel, biofuel, electricity, or hydrogen production (“well-to-tank,” WTT) and the emissions of fossil fuel combustion in the vehicle (“tank-to-wheel,” TTW). For fossil fuels, as displayed in Table 2, the scope of this analysis covers crude oil extraction (including flaring), processing and transport, fuel refining and distribution, all associated methane leakage, and the combustion of fuels in internal combustion engines. We also account for methane and nitrous oxide emissions during the combustion of fossil fuels and biofuels. For biofuels, the scope covers emissions of plant cultivation, plant processing and transport, and from biofuel production and distribution. The $CO_2$ emissions of biofuel combustion are not considered, as these are offset by biogenic $CO_2$ uptake during the growth of plants.

For biofuels production, this analysis also shows the direct land use change (DLUC) emissions that correspond to the domestic expansion of area used for agriculture. These emissions reflect the clearing of above-ground biomass and the change of soil carbon that happens when converting natural vegetation to agriculture. Indirect land use change emissions, which consider the broader effect of an increase in biofuel production on the global conversion of land, are not included.

The life-cycle emissions of electricity cover the upstream and direct emissions of electricity generation, new power plant infrastructure for renewable energy, and the energy loss in transmission and distribution in the electric grid. The carbon intensity of the fuel and electricity considers the current biofuel blends and electricity mix in Indonesia and future projections for each under different scenarios during the vehicles’ lifetimes.

For hydrogen, the analysis distinguishes between natural gas-, coal-, and electricity-based hydrogen. For natural gas- and coal-based hydrogen, the extraction, processing, and transport of the fossil fuel and emissions during the steam reforming or coal gasification processes are accounted for, all including methane emissions. The assessment of electricity-based hydrogen considers the life-cycle GHG emissions of electricity generation and the energy losses during electrolysis. All hydrogen pathways consider hydrogen compression and the energy losses for short-distance transportation. The energy losses of long-distance transport of hydrogen, such as from a different continent, are not included.

**Table 2.** Scope of the GHG emissions in the fuel and electricity cycle.

| Data | Summary of scope |
|---|---|
| **Fossil fuels** | Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution; $CO_2$ and non-$CO_2$ GHG emissions of fuel consumption, including methane and nitrous oxide emissions from the vehicle |
| **Biofuels** | Plant cultivation/waste collection, processing and transport, fuel production and distribution; direct land use change GHG emissions of plant cultivation; non-$CO_2$ GHG emissions of fuel consumption, including methane and nitrous oxide emissions from the vehicles |
| **Electricity** | Life-cycle GHG emissions of electricity generation (including power plant infrastructure), transmission, distribution and charging losses; direct land use change GHG emissions of biomass used for electricity generation |
| **Hydrogen** | Electrolysis-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression; natural gas- and coal-based hydrogen: natural gas/coal extraction, processing and transport, steam reforming/ coal gasification and hydrogen compression, all steps including methane leakage |

This study does not cover GHG emissions corresponding to the construction and maintenance of vehicle production infrastructure, infrastructure for vehicle fueling and charging, or road infrastructure.

## SELECTION OF REPRESENTATIVE VEHICLE MODELS

The study is based on vehicle models that are representative for A segment cars, SUVs, and MPVs in Indonesia. Two-wheelers are compared based on representative models in the scooter segment. The following sections describe how the representative vehicle models were selected.

### Passenger cars

Data from MarkLines (2022) shows that in 2021, 821,000 new four-wheeler light-duty vehicles were sold in Indonesia; most of these can be classified as MPVs (38%), SUVs (27%), and A segment cars (10%).[1] Most four-wheeler light-duty vehicles in Indonesia are gasoline-powered ICEVs—87% in 2019—and diesel-powered ICEVs make up most of the rest (13%); HEVs were only 0.1% of sales that year (IEA, 2021). The share of BEVs in new car sales in Indonesia was 0.01% in 2019 and that increased to 0.1% in 2022; PHEVs and FCEVs were hardly sold (EV-volumes, 2022). For a representative comparison of the different power trains, the analysis starts with popular gasoline ICEV models and compares them with similar diesel ICEV, HEV, PHEV, BEV, and FCEV models sold in Indonesia where applicable. All selected models and their specifications are displayed in Table 3.

For gasoline ICEVs, the Honda Brio was selected in the A segment, as it is the most popular model and was 52% of 2021 sales in this segment (MarkLines, 2022). The Toyota Rush, which is also sold in Indonesia as the Daihatsu Terios, was 32% of new SUV sales in 2021 (MarkLines, 2022) and was chosen as the representative gasoline ICEV model for the segment. In the MPV segment, the Toyota Innova was selected as the representative gasoline ICEV; it was 16% of new sales in the segment in 2021 (MarkLines, 2022) and a diesel variant is available.

As options for diesel ICEV models in the A segment are limited in Indonesia, no representative model could be chosen. In the SUV segment, the Kia Seltos was selected as a representative diesel ICEV because its engine power, vehicle weight, and vehicle footprint are similar to those of the Toyota Rush. For the MPV segment, the gasoline-powered Toyota Innova is compared to the diesel-powered variant.

1 These are the segments assigned by MarkLines. They resemble international car segmentation systems. In 2021, the most popular vehicle models in the A, B, and C segments were the Honda Brio, Toyota Vitz (Yaris), and Honda City, respectively. In the SUV and MPV segments, the most popular models were the Toyota Rush and Toyota Avanza.

HEVs and PHEVs are only compared in the SUV segment, as no models are sold in Indonesia in either the MPV segment or the A segment. For HEVs, the most popular SUV model in 2021 was the Toyota Corolla Cross, which was 64% of new HEV sales in the segment (Gabungan Industri Kendaraan Bermotor Indonesia [GAIKINDO], 2023a; MarkLines, 2022). For PHEVs, the only SUV model sold in 2021 was the Mitsubishi Outlander (EV-volumes, 2022).

For BEVs, the Hyundai Kona was the only SUV model sold in Indonesia in 2021 and it was 42% of total BEV sales that year (EV-volumes, 2022). Similarly, in the MPV segment, the BYD e6 was the only battery electric model sold in Indonesia in 2021 (vehicles of this model were only available for a taxi company). In the A segment, although no BEV model was sold in 2021, in 2022, the domestically produced Wuling Air EV was introduced and more than 8,000 vehicles were sold; this was the most popular BEV model in Indonesia in 2022 and it was 78% of new BEV sales in all segments that year (GAIKINDO, 2023b). The Wuling Air EV was selected as a BEV comparator, even though it has lower engine power and a smaller vehicle footprint than the Honda Brio. The Hyundai Nexo was selected as the FCEV model for the SUV segment even though it was not sold in Indonesia in 2021.

**Table 3.** Vehicle characteristics of the selected models in the three segments.

| Segment | Power train type | Model name | Engine power (kW) | Curb weight (kg) | Footprint [a] (m²) |
|---|---|---|---|---|---|
| A segment | Gasoline ICEV | Honda Brio | 65 | 920 | 3.5 |
| | BEV | Wuling Air EV | 30 | 890 | 2.8 |
| SUV | Gasoline ICEV | Toyota Rush | 78 | 1,245 | 3.9 |
| | Diesel ICEV | Kia Seltos | 85 | 1,340 | 4.1 |
| | HEV | Toyota Corolla Cross | 72 + 53 [b] | 1,385 | 4.1 |
| | BEV | Hyundai Kona | 100 | 1,610 | 4.1 |
| | PHEV | Mitsubishi Outlander | 87 + 120 [b] | 1,880 | 4.1 |
| | FCEV | Hyundai Nexo | 113 | 1,814 | 4.5 |
| MPV | Gasoline ICEV | Toyota Innova | 102 | 1,735 | 4.2 |
| | Diesel ICEV | Toyota Innova | 110 | 1,855 | 4.2 |
| | BEV | BYD e6 | 90 | 1,930 | 4.3 |

[a] Vehicle footprint is defined by the vehicle wheelbase and axle width.
[b] Internal combustion engine power and electric motor power.

### Two-wheelers

In 2021 and 2022, more than 5 million new two-wheelers were sold in Indonesia (Motorcycles Data, 2023). In 2020, sales were lower, at 3.7 million (Le & Yang, 2022). A large majority of the two-wheelers sold in these years were scooters (84% in 2020). The remainder were motorcycles. With 41,000 new electric two-wheelers, almost all of them scooters, sold in 2020, the electric vehicle sales share was about 1%. The remainder of new two-wheelers sold were gasoline powered. In the scooter segment, 76% of these gasoline vehicles have an engine displacement below 125 $cm^3$. The Honda Beat was the most popular model in this category, with 44% of sales in 2020. For its electric counterpart, we selected the Gesits G1 because it was 66% of electric scooter sales in 2020.

**Table 4.** Vehicle characteristics of the selected scooter models.

| Segment | Power train type | Model name | Engine power (kW) | Curb weight (kg) |
|---|---|---|---|---|
| Scooter | Gasoline ICEV | Honda Beat | 6.6 | 89 |
| | BEV | Gesits G1 | 5.0 | 95 |

## VEHICLE CYCLE

### Glider and power train

For passenger cars, the GHG emissions corresponding to the production and recycling of the glider and power train are derived from the power train-specific, vehicle-mass-dependent factors from Hill et al. (2020) and corrected for the mass of the glider and power train of each selected vehicle model. The mass of the glider and power train is equal to the vehicle mass without the battery weight. The weight of the battery is estimated from the battery capacity (see Table 6, below) and a specific energy of the battery pack of 148 Wh/kg (Hill et al., 2020). For two-wheelers, vehicle-mass-dependent emission factors for the glider and power train are derived from Carranza et al. (2022). The total emissions in t $CO_{2\ eq.}$ are shown in Table 5.

**Table 5.** GHG emissions of the production and recycling of the glider and power train, and of maintenance of the selected models sold in 2023.

| Vehicle type | Segment | Powertrain | Model name | Vehicle production and recycling (t $CO_{2\ eq.}$) | Maintenance (g $CO_{2\ eq.}$/km) |
|---|---|---|---|---|---|
| Passenger car | A segment | Gasoline ICEV | Honda Brio | 4.7 | 4.4 |
| | | BEV | Wuling Air EV | 3.6 | 3.5 |
| | SUV | Gasoline ICEV | Toyota Rush | 6.6 | 4.9 |
| | | Diesel ICEV | Kia Seltos | 7.1 | 6.4 |
| | | HEV | Toyota Corolla Cross | 7.5 | 5.2 |
| | | PHEV | Mitsubishi Outlander | 10.2 | 6.0 |
| | | BEV | Hyundai Kona | 7.2 | 3.6 |
| | | FCEV | Hyundai Nexo | 8.8 | 3.5 |
| | MPV | Gasoline ICEV | Toyota Innova | 9.8 | 5.7 |
| | | Diesel ICEV | Toyota Innova | 10.4 | 8.1 |
| | | BEV | BYD e6 | 7.8 | 3.7 |
| Two-wheeler | Scooter | Gasoline ICEV | Honda Beat | 0.3 | 1.9 |
| | | BEV | Gesits G1 | 0.4 | 1.0 |

For vehicles sold in 2030, the weight of the glider and power train is assumed to be the same as for the 2023 models. Due to a projected decarbonization of the industry and power sectors, the emissions displayed in Table 5 are assumed to be 15% lower (Bieker, 2021a; Hill et al., 2020).

### Battery

Table 6 shows GHG emissions from producing batteries for current electric vehicles. They are derived from the battery capacities of the considered models and a GHG emissions factor of 56 kg $CO_{2\ eq.}$ per kWh of battery capacity. This factor corresponds to the carbon intensity of lithium iron phosphate (LFP)-based batteries produced in China (Bieker, 2021a) and is based on the GREET model (Argonne National Laboratory, 2020). This variant of lithium-ion batteries is assumed for all vehicles in this study, as it is the most common in Indonesia. For reference, the emissions for lithium nickel manganese cobalt oxide (NMC622)-based batteries produced in China are 69 kg $CO_{2\ eq.}$/kWh.

This study assumes batteries last longer than the lifetime of vehicles. This is based on studies showing that state-of-the-art lithium-ion batteries offer 90%–95% of the initial capacity even after 3,000 full cycles of fast charge and discharge (Harlow et al., 2019). With real-world ranges of 200 km to 400 km for electric cars, the 3,000 cycles correspond to a mileage of 600,000 km to 1,200,000 km. For electric scooters, a range of 40 km to 50 km corresponds to a battery lasting for 120,000 km to

150,000 km. These numbers exceed the lifetime mileage discussed below, especially for passenger cars. (Still, we also show a sensitivity analysis for the case in which replacement of the battery is needed, in the description of results below.)

The GHG emission benefits of a potential second-life use, for instance as stationary storage for the electric grid, and the GHG emission benefits from battery recycling (see Tankou et al., 2023), are not considered.

**Table 6.** Battery capacity and GHG emissions from battery production for the selected PHEV, BEV, and electric two-wheeler models.

| Vehicle type | Segment | Power train | Model name | 2023 vehicle model | | 2030 vehicle model | |
|---|---|---|---|---|---|---|---|
| | | | | Gross capacity (kWh) | GHG emissions (t $CO_{2\ eq.}$) | Gross capacity (kWh) | GHG emissions (t $CO_{2\ eq.}$) |
| **Passenger car** | A segment | BEV | Wuling Air EV | 26.7 | 1.5 | 32.0 | 1.4 |
| | SUV | PHEV | Mitsubishi Outlander | 12.0 | 0.7 | 12.0 | 0.5 |
| | | BEV | Hyundai Kona | 39.2 | 2.2 | 47.0 | 2.1 |
| | MPV | BEV | BYD e6 | 71.7 | 4.0 | 86.0 | 3.9 |
| **Two-wheeler** | Scooter | BEV | Gesits G1 | 1.4 | 0.1 | 1.7 | 0.1 |

For hypothetical 2030 vehicle models, the emissions factor to produce lithium-ion batteries is reduced to 45 kg $CO_{2\ eq.}$ per kWh. This is based on a general assumption about the reduction of the carbon intensity of battery production by 20% (Bieker, 2021a). For future BEV models, battery capacity is assumed to increase by 20% because of lower production costs.

### Hydrogen system

GHG emissions corresponding to hydrogen fuel tanks and fuel cells are obtained from the GREET model (Argonne National Laboratory, 2020). For fuel cell electric SUVs, the model provides emissions of 4.2 t $CO_{2\ eq.}$; that is used for the Hyundai Nexo in this study. As discussed by Bieker (2021a), similar values are used in other LCA studies (Agora Verkehrswende, 2019; Fraunhofer Institute for Systems and Innovation Research ISI, 2019; Hill et al., 2020).

### Lifetime mileage

We compare life-cycle GHG emissions of electric and combustion engine vehicles by considering the same average use case. For passenger cars, average annual mileage is assumed to be 13,600 km, as considered by the state-owned electricity supplier Perusahaan Listrik Negara (PLN) in the Rencana Usaha Penyediaan Tenaga Listrik (RUPTL), the National Electricity Supply Business Plan 2021-2030 (Government of Indonesia and PLN, 2021). Combined with our assumption of an average vehicle lifetime of 18 years, this results in a lifetime mileage of 244,800 km. The assumed vehicle lifetime of 18 years is considered a conservative estimate. The National Energy Council stated that limiting the age of passenger cars allowed on the road in Indonesia to 25 years would result in quicker fleet turnover (National Energy Council, 2019). This suggests a large portion of the vehicle fleet was expected to be older than 25 years. Another study considered the same effect on turnover by limiting the maximum vehicle age to 19 years (Deendarlianto et al., 2020).

For two-wheelers, an average annual mileage of 8,300 km/year is used (based on Heidt et al., 2019). The vehicle lifetime is assumed to be 12 years, using the same value considered in an earlier LCA study for two-wheelers in India (Anup et al., 2021; Bieker, 2021b). For reference, Cox and Mutel (2018) reported 10–12 years of use for two-wheelers in Switzerland and for two-wheelers in Indonesia, Sopha et al. (2016) assumed a lifetime of 13 years. With the proposed values, the lifetime mileage of two-wheelers is 99,600 km.

As vehicles generally tend to have higher annual mileage in early years than in later years, the annual mileage per individual vehicle is assumed to decrease for older cars by 5% per year, based on data from Germany (Bieker, 2021a). This also means that the carbon intensity of the fuel and electricity mix is weighted more heavily in earlier years.

## Maintenance

As discussed by Bieker (2021a), combustion engine vehicles generally require more maintenance than electric vehicles. They thus also correspond to slightly higher GHG emissions associated with maintenance. To account for GHG emissions from maintenance, the emissions factors specific to the power train and vehicle weight are derived from Hill et al. (2020) for passenger cars and Carranza et al. (2022) for two-wheelers. These are scaled with the weight of the considered vehicle models. The derived distance-specific factors (in g $CO_{2\ eq.}$/km) are shown in Table 5.

## FUEL AND ELECTRICITY CYCLE

### Real-world fuel and electricity consumption

Table 7 shows the official test cycle fuel or electricity consumption for the selected vehicle models (recall that Tables 3 and 4 contain vehicle specifications). As vehicle manufacturers are not required to publicly report fuel/electricity consumption or $CO_2$ emissions of vehicles in Indonesia, the fuel and electricity consumption values in Table 7 correspond to vehicles with the same model name and year, engine capacity, and engine power sold in other markets.

The official fuel consumption values of the selected vehicle models were slightly lower than the segment-average fuel consumption of vehicles sold in Indonesia in 2019 (IEA, 2021). For A segment gasoline ICEVs, the official fuel consumption of the Honda Brio of 5.4 L/100 km in the Modified Indian Driving Cycle (MIDC) is slightly lower than the 2019 A segment average of 6.2 L/100 km (adjusted to MIDC), and the 6.9 L/100 km for the Toyota Rush in the New European Driving Cycle (NEDC) is lower that the 7.3 L/100 km for average gasoline ICEVs in the small SUV segment (IEA, 2021). The selection of the most popular vehicles in these segments is thus considered to underestimate the emissions of average gasoline vehicles.

To reflect real-world driving conditions, the official fuel and electricity consumption for passenger cars is adjusted by test cycle- and power train type-specific correction factors. While for gasoline ICEVs, the real-world fuel consumption has been found to be, on average, 37% higher than official NEDC values, the deviation is 44% for diesel ICEVs and 50% for HEVs (Dornoff et al., 2020; Yang & Yang, 2018). For vehicles type-approved with the MIDC, the deviation is assumed to be similar to NEDC tested vehicles. Note that the official fuel consumption values further correspond to the reference fuel used in the type-approval process of their respective country. Based on the respective energy density (in MJ/L), these values are adjusted to the energy density of Indonesia’s fuel mix.

For BEVs, the real-world electricity consumption is considered to be, on average, about 19% higher than Worldwide Harmonized Light-duty Vehicle Test Procedure (WLTP) values (Allgemeiner Deutscher Automobil-Club [ADAC], 2021; van Gijlswijk et al., 2022). While the WLTP electricity consumption value is available for the Hyundai Kona, it is estimated for the BYD e6 by dividing 95% of the gross battery capacity by the WLTP range and adding 15% due to charging losses. For the Wuling Air EV, where the NEDC value for the range is available, the real-world electricity consumption is estimated as described for the BYD e6, but by applying 43% as an NEDC to real-world correction factor. For the real-world hydrogen consumption of the Hyundai Nexo, the value determined in the independent vehicle tests of the ADAC Ecotest is considered (ADAC, 2021), and it is about 50% higher than the official NEDC value.

The fuel and electricity consumption of the Mitsubishi Outlander PHEV is based on the fuel consumption in charge-sustaining mode, when the vehicle is predominantly powered by the combustion engine, and the electricity consumption in electric charge-depleting mode, when it is mainly running on battery power, both as determined for the U.S. Environmental Protection Agency (U.S. EPA) label values (U.S. EPA & U.S. Department of Energy, 2022). The share of driving in these modes is assumed to be 50%, which is based on an electric driving share for this model observed in real-world operation in Europe (Plötz et al., 2022). Note that in the United States, the electric driving share of this model is observed to be only about 40% (Isenstadt et al., 2022).

**Table 7.** Real-world fuel, electricity, and hydrogen consumption of the selected vehicle models.

| Vehicle type | Segment | Power train | Model name | Official test cycle consumption (L/100 km, kWh/100 km, or kg/100 km) | Official test cycle | Real-world fuel or hydrogen consumption (L/100 km or kg/100 km) | Real-world electricity consumption (kWh/100 km) | Real-world energy consumption (MJ/km) |
|---|---|---|---|---|---|---|---|---|
| Passenger car | A segment | **Gasoline ICEV** | Honda Brio | 5.4 [a] | MIDC | 7.4 | — | 2.4 |
| | | **BEV** | Wuling Air EV | | | — | 13.9 [b] | 0.5 |
| | SUV | **Gasoline ICEV** | Toyota Rush | 6.9 [c] | NEDC | 9.4 | — | 3.0 |
| | | **Diesel ICEV** | Kia Seltos | 5.6 [a] | MIDC | 8.0 | — | 2.9 |
| | | **HEV** | Toyota Corolla Cross | 4.3 [d] | NEDC | 6.5 | — | 2.1 |
| | | **PHEV** | Mitsubishi Outlander | | | 4.5 [e] | 14.0 [e] | 1.5 + 0.5 |
| | | **BEV** | Hyundai Kona | 14.3 [f] | WLTP | — | 17.0 | 0.6 |
| | | **FCEV** | Hyundai Nexo | 0.8 [g] | NEDC | 1.2 | — | 1.4 |
| | MPV | **Gasoline ICEV** | Toyota Innova | 9.1 [h] | NEDC | 12.5 | — | 4.0 |
| | | **Diesel ICEV** | Toyota Innova | 6.7 [a] | MIDC | 9.7 | — | 3.4 |
| | | **BEV** | BYD e6 | 19.7 [i] | WLTP | — | 23.4 | 0.8 |
| Two-wheeler | Scooter | **Gasoline ICEV** | Honda Beat | | | 2.3 | — | 0.7 |
| | | **BEV** | Gesits G1 | | | — | 6.2 | 0.2 |

[a] Data from India, source: Segment Y Automotive Intelligence
[b] Based on NEDC range data from Wuling Indonesia, https://wuling.id/id
[c] Data from Chile, source: https://www.consumovehicular.cl
[d] Data from the Philippines, source: https://toyotasantarosa.com.ph/toyota-crosses-into-a-bold-direction-with-all-new-toyota-corolla-cross
[e] Fuel and electricity consumption estimated with U.S. EPA label fuel consumption in charge-sustaining mode and electricity consumption in charge-depleting mode, weighted by a 50% electric driving share
[f] Global data, source: EV-volumes
[g] Data from Germany, source: ADAC (2021)
[h] Data from Malaysia, source: https://www.wapcar.my/cars/toyota/innova/specs
[i] Based on WLTP range data from Singapore, source: https://sg.byd.com/electrical-vehicles/all-new-e6/

Regarding two-wheelers, real-world fuel consumption of the Honda Beat is obtained from consumer reported values on the website fuelly.com, specifically from users from Southeast Asian countries in 2020 and 2021 (Fuelly, 2022). For the real-world electricity consumption of the Gesits G1, data from real driving tests on Indonesian streets by Yuniarto et al. (2022) is used. As Yuniarto et al. (2022) did not include energy losses during battery charging, in this study, the reported electricity consumption value is increased by 15%.

For hypothetical vehicle models sold in 2030, fuel, electricity, and hydrogen consumption are assumed to remain the same as today's vehicles. This is because there have been no improvements in fuel consumption in Indonesia in recent years (IEA, 2021) and no fuel economy standards are yet in place.

## GHG emissions of the gasoline, diesel, and biofuel blends

The Rencana Umum Energi Nasional, the General Plan for National Energy, targets high shares of biofuels in the average fuel blend (Government of Indonesia, 2014). By 2020, the ethanol share was supposed to increase to 10% by volume and reach 20% in 2035. However, this mandate has not been enforced and the share of ethanol in the average gasoline blend in Indonesia remains negligible (U.S. Department of Agriculture, 2022). This study thus assumes that the ethanol share will remain at 0% until 2050.

For biodiesel, the regulatory target is set at 35% by volume from 2023 by Decree No. 208.K/EK.05/DJE/2022 (Ministry of Energy and Mineral Resources, 2023) and is supposed to stay at this level until 2050. Unlike for ethanol, biodiesel blending rates were met in the past years (U.S. Department of Agriculture, 2022). Therefore, the targeted biodiesel share of 35% (B35) is considered as the Baseline scenario for the diesel blend. In Indonesia, this biodiesel blend solely consists of fatty acid methyl ester (FAME) made from palm oil. For biodiesel, an alternative scenario addresses the ongoing discussions regarding increasing the blending mandate to 40% biodiesel (B40). It is assumed that this share would be met starting in 2025 and remain at this level until 2050.

For fossil gasoline and diesel, the upstream WTT emissions, which mostly correspond to petroleum extraction, processing, and transport, and the TTW emissions from the fuel combustion in the vehicles are obtained from Bieker (2021a). While the TTW emissions are based on a report by a consortium of the European Commission's Joint Research Centre, EUCAR, and Concawe (Prussi et al., 2020), the WTT emissions are derived by combining them with the WTW emissions considered by the European Union's Fuel Quality Directive (Council of the European Union, 2015) and the U.S. Renewable Fuel Standard Program (U.S. EPA, 2010).

As the production of biodiesel from palm oil requires that additional land be used for agriculture, this study considers DLUC emissions. Following the IPCC's methodologies (IPCC, 2019), we consider that during land conversion, all carbon contained in the above-ground biomass is emitted in the form of $CO_2$. In addition, we assume that 22% of soil organic carbon is emitted; this is a low-range estimate from the literature and based on meta-analyses conducted by Murty et al. (2002) and Guo and Gifford (2002). Land type-specific above-ground biomass data are taken from the IPCC (2019), and soil carbon data is taken from the Harmonized World Soil Database published by the Food and Agricultural Organization of the United Nations (FAO) and other international research organizations (FAO, 2008). These values are weighted with the shares of land types that have been converted for palm oil production in Indonesia in the past (Austin et al., 2017). As recommended by IPCC guidelines, land use change emissions are allocated over a period of 20 years and emissions are divided by the output of biofuel (in MJ) over that period. The output is based on crop yield data from the FAO's statistical database on food and agricultural products (FAO, 2023) and feedstock-to-fuel conversion factors from GREET tool (Argonne National Laboratory, 2022).

Table 8 presents the WTT, DLUC, and TTW emissions of the individual fossil and biofuel pathways, and the emissions of the B35 and B40 fuel blends considered in this study. Note that the energy content, as expressed by the lower heating value (LHV, in MJ/L), differs among the individual fuel pathways and blends. As these values are generally lower for ethanol and biodiesel, the overall fossil and biofuel blends also have a lower LHV than the pure fossil fuels.

**Table 8.** Fuel cycle (WTT, DLUC, and TTW) emissions of fossil gasoline and diesel and biofuel blend targets.

| Fuel | Source | LHV (MJ/L) | GHG emissions: WTT (excluding DLUC) ($g\ CO_{2\ eq.}/MJ$) | DLUC ($g\ CO_{2\ eq.}/MJ$) | TTW ($g\ CO_{2\ eq.}/MJ$) |
|---|---|---|---|---|---|
| **Fossil gasoline** | **Fossil** | 32.1 | 19.9 | 0 | 73.4 |
| **Fossil diesel** | **Fossil** | 35.9 | 21.9 | 0 | 73.2 |
| **Biodiesel** | **Palm oil** | 33.1 | 44.5 | 111.3 | — |
| **B35** | **Fossil and palm oil** | 34.9 | 29.4 | 37.0 | 48.9 |
| **B40** | **Fossil and palm oil** | 34.8 | 30.5 | 42.4 | 45.3 |

In the alternative scenario for the future biodiesel blend, the fuel mix changes during the lifetime of the vehicles. Thereby, the overall carbon intensity of the fuel mix changes. Table 9 presents the lifetime average emission factors of fuels for passenger cars used from 2023 to 2040 and from 2030 to 2047, and for two-wheelers used from 2023 to 2034 and from 2030 to 2041. Note that these numbers account for decreasing annual mileage.

**Table 9.** Lifetime average WTT, DLUC, TTW, and overall fuel cycle (WTW) emissions of the fuel used in 2023 and 2030 passenger cars and two-wheelers in Indonesia.

| Fuel scenario | 2023 vehicles: WTT (excluding DLUC) ($g\ CO_{2\ eq.}/MJ$) | 2023 vehicles: DLUC ($g\ CO_{2\ eq.}/MJ$) | 2023 vehicles: TTW ($g\ CO_{2\ eq.}/MJ$) | 2023 vehicles: WTW ($g\ CO_{2\ eq.}/MJ$) | 2030 vehicles: WTT (excluding DLUC) ($g\ CO_{2\ eq.}/MJ$) | 2030 vehicles: DLUC ($g\ CO_{2\ eq.}/MJ$) | 2030 vehicles: TTW ($g\ CO_{2\ eq.}/MJ$) | 2030 vehicles: WTW ($g\ CO_{2\ eq.}/MJ$) |
|---|---|---|---|---|---|---|---|---|
| **Gasoline** | 19.9 | — | 73.4 | 93.3 | 19.9 | — | 73.4 | 93.3 |
| **Diesel (B35)** | 29.4 | 37.0 | 48.9 | 115.3 | 29.4 | 37.0 | 48.9 | 115.3 |
| **Diesel (B40)** | 30.4 | 41.9 | 45.7 | 118.0 | 30.5 | 42.4 | 45.3 | 118.2 |

Because fuel combustion in internal combustion engines is not always complete and because of the action of aftertreatment on exhaust gases, some methane and nitrous oxide emissions are produced in vehicles, as described in detail in Bieker (2021a). Such emissions add, on average, about 1 $g\ CO_{2\ eq.}$/km of TTW GHG emissions for gasoline and 4 $g\ CO_{2\ eq.}$/km for diesel cars (Bieker, 2021a). These emissions were added to the emissions displayed in Table 9.

## GHG emissions of electricity

The future development of the average electricity mix in Indonesia is estimated based on a conservative Baseline scenario and a more optimistic alternative scenario that we call the Net-zero 2060 scenario. The Baseline scenario reflects the targets of the 2014 Kebijakan Energi Nasional, the National Energy Policy, which were also stated in the 2017 Rencana Umum Energi Nasional, the National Energy Plan (Government of Indonesia, 2014): a 23% share of renewables in the total energy supply by 2025 and a 31% share by 2050. Figure 2 presents how these targets translate into the development of the electricity mix. Until 2030, the “optimal scenario” in the Rencana Usaha Penyediaan Tenaga Listrik, the National Electricity Supply Business Plan 2021-2030 (Government of Indonesia and PLN, 2021), projects attaining a 23% share of renewables. For the extended period until 2050, the development is projected based on the “business as usual” scenario in the Indonesia Energy Outlook 2019 (National Energy Council, 2019). In addition to the small increase in the share of renewables up to 27%, the Baseline scenario considers an increasing share of natural gas up to 32% in 2050.

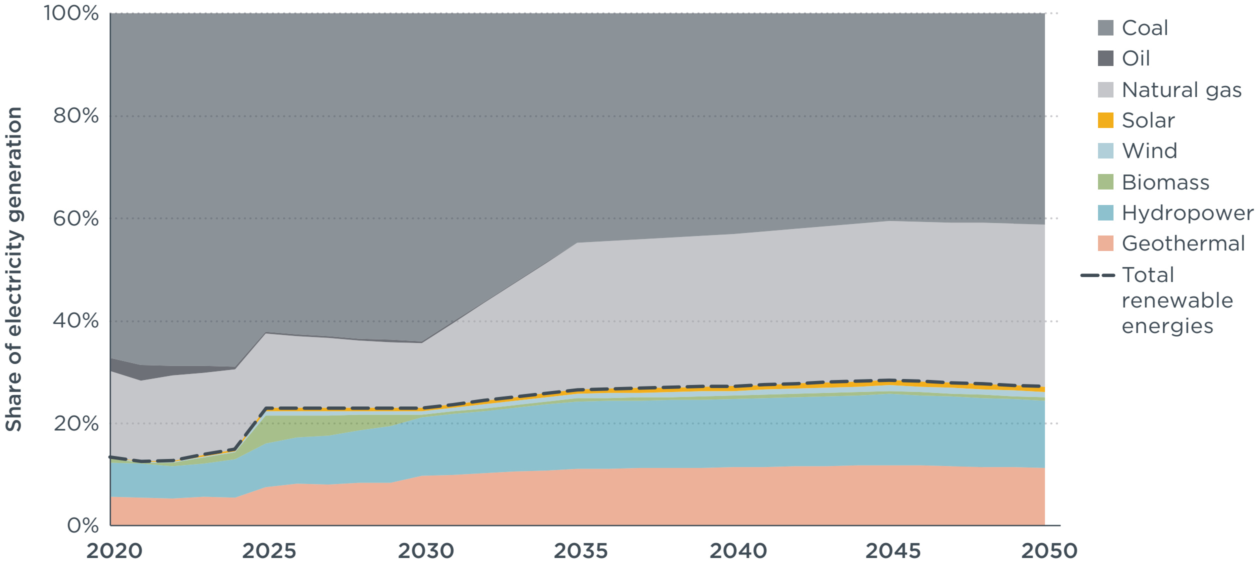



**Figure 2.** Projected shares of technologies in electricity generation in Indonesia under the Baseline scenario.

The alternative Net-zero 2060 scenario reflects the Government of Indonesia's target of reaching net zero emissions by 2060 "or sooner," as outlined in the Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Government of Indonesia, 2021). It is based on the IEA's Announced Pledges Scenario (IEA, 2022a), which is a result of the joint work of the IEA and the Indonesian Ministry of Energy and Mineral Resources.[2] As shown in Figure 3, the Net-zero 2060 scenario considers a large reduction in the use of fossil fuels and an increase in the share of renewable sources to 89% by 2050. This expected increase in renewables is driven by the continuously falling costs of solar and wind power and by government targets.

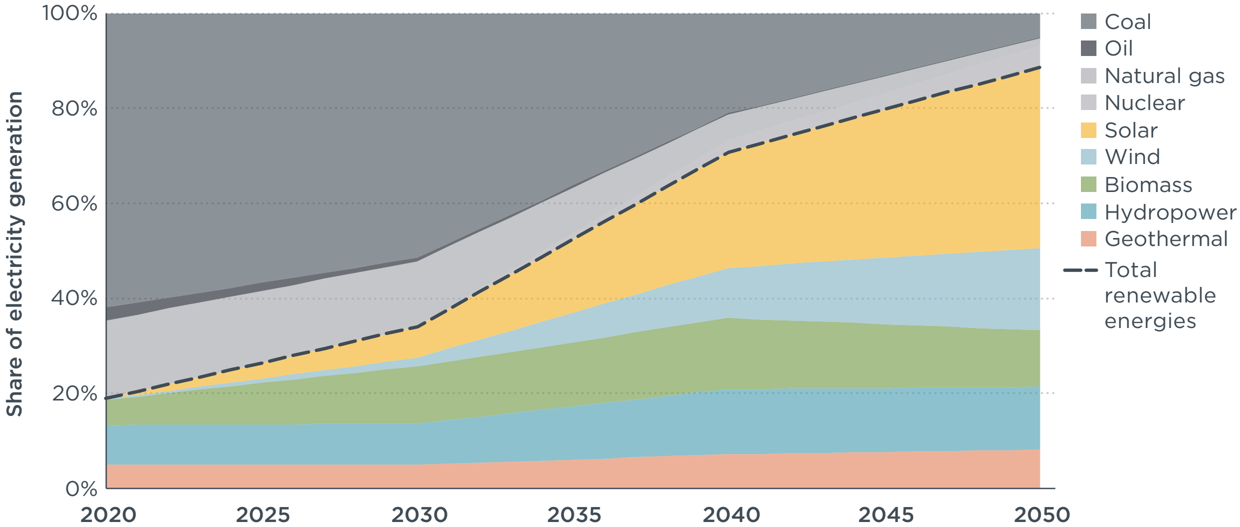



**Figure 3.** Projected shares of technologies in electricity generation in Indonesia under the Net-zero 2060 scenario.

Based on weighting the shares of electricity-generation technologies in the Baseline and Net-zero 2060 scenarios by the IPCC's global median life-cycle carbon intensity factors, Figure 4 presents the development of the life-cycle GHG emissions of the

2 In a conservative approach, the GHG emissions of coal power with carbon capture, utilization, and storage (CCUS) are considered with the same carbon intensity as unabated coal power. The small share of electricity generation from hydrogen is removed from the original scenario.

average electricity mix in Indonesia from 2020 to 2050. To account for the energy losses in the grid, it includes transmission and distribution losses of 8.6% (Ministry of Energy and Mineral Resources, 2022).

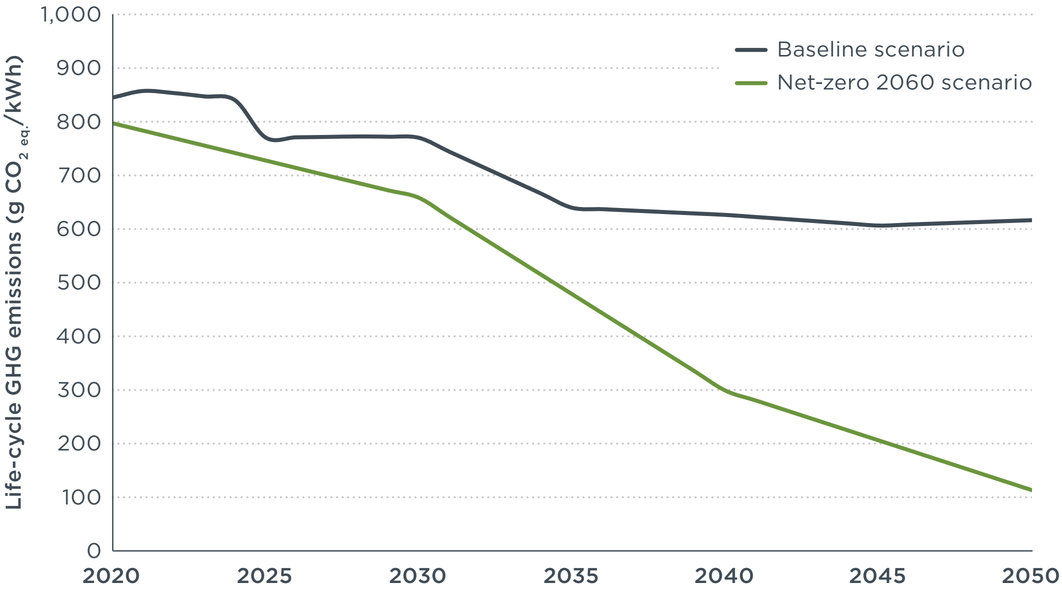



**Figure 4.** Development of the life-cycle GHG emissions for the average electricity mix in Indonesia from 2020 to 2050 under the Baseline and Net-zero 2060 scenarios.

The IPCC's global median emission factors for electricity generation (Moomaw et al., 2011) are presented in Table A1 in the Appendix. They cover upstream emissions and the emissions of the construction of new power plants throughout their lifetimes as a function of the electricity generated. Using a conservative approach, no reduction in these factors for future years is included, even though the ongoing decarbonization of industry will reduce the emissions of renewable power plant manufacturing (Pehl et al., 2017). As the IPCC's life-cycle GHG emission factors for electricity-generation technologies do not include land use change emissions, the value for biomass-based electricity production is adjusted to 230 g $CO_{2\ eq.}$/kWh, based on Christensen and Petrenko (2017), to include land use change emissions.

Table 10 presents the lifetime average carbon intensity of the electricity consumption of passenger cars driven from 2023 to 2040 and from 2030 to 2047, and of two-wheelers driven from 2023 to 2034 and from 2030 to 2041. These numbers consider the annual development of the life-cycle carbon intensity of electricity consumption and the decreasing annual vehicle mileage. As vehicles tend to have a higher annual mileage in their early years of use, the carbon intensity of the electricity mix is weighted more heavily in the early years. In addition, a purely renewable electricity mix is considered with a mix of solar (67%) and wind energy (33%), with life-cycle GHG emissions of 35 g $CO_{2\ eq.}$/kWh. Energy losses during vehicle charging are already accounted for in the real-world electricity consumption values discussed above.

**Table 10.** Average life-cycle GHG emissions of electricity mix scenarios during the lifetime of 2023 and 2030 passenger cars and two-wheelers in Indonesia.

| Vehicle type | Electricity mix scenario | 2023 vehicles | | 2030 vehicles | |
|---|---|---|---|---|---|
| | | (g $CO_{2\ eq.}$/kWh) | | (g $CO_{2\ eq.}$/kWh) | |
| Passenger cars | **Baseline** | 737 | 2023–2040 electricity mix | 661 | 2030–2047 electricity mix |
| | **Net-zero 2060** | 607 | 2023–2040 electricity mix | 421 | 2030–2047 electricity mix |
| Two-wheelers | **Baseline** | 770 | 2023–2034 electricity mix | 676 | 2030–2041 electricity mix |
| | **Net-zero 2060** | 674 | 2023–2034 electricity mix | 484 | 2030–2041 electricity mix |

## GHG emissions of hydrogen

This study compares the life-cycle GHG emissions of FCEVs using hydrogen produced from the most common pathways of coal gasification (black hydrogen) and steam reforming of natural gas (grey hydrogen) with electrolysis-based hydrogen from the average grid mix and solely from additional renewable electricity (green hydrogen). While hydrogen produced from natural gas was 62% of global production in 2021 and coal-based hydrogen was 19%, the share of electricity-based hydrogen was 0.04% (IEA, 2022b). During the next decades, however, electricity-based hydrogen is expected to become dominant. For the 2023 SUV, Table 11 shows the GHG emissions of producing hydrogen via the three pathways (in kg $CO_{2\ eq.}$ per kg of hydrogen).

As discussed in Bieker (2021a), the life-cycle GHG emissions of coal- and natural gas-based hydrogen are based on the GREET model (Argonne National Laboratory, 2020). For electricity-based hydrogen, the life-cycle GHG emissions of electricity production and the energy losses during electrolysis and hydrogen compression are considered. All pathways include the emissions corresponding to the compression and short-distance transport of hydrogen. The energy losses of long-distance transport, in other words, for hydrogen produced on a different continent, are not addressed in this study.

**Table 11.** Life-cycle GHG emissions of different hydrogen pathways in combination with electricity mix scenarios during the lifetime of 2023 new passenger cars.

| Source or technology | Electricity mix | GHG production emissions (kg $CO_{2\ eq.}$/kg $H_2$) |
|---|---|---|
| **Coal** | Baseline | 24.3 |
| **Natural gas** | Baseline | 12.9 |
| **Electrolysis** | Baseline | 41.3 |
| | Net-zero 2060 | 34.0 |
| | Renewables | 1.9 |

# RESULTS

## PASSENGER CARS

### 2023 passenger cars

Figures 5, 6, and 7 present the life-cycle GHG emissions (in g $CO_{2\ eq.}$/km) for A segment passenger cars, SUVs, and MPVs, respectively, over the lifetime of vehicles produced today. The figures distinguish between the GHG emissions of vehicle production (the production of the battery and the rest of the vehicle) and the GHG emissions during the use phase, which correspond to the fuel and electricity production, vehicle fuel consumption, and maintenance. Direct land use change GHG emissions are presented separately.

The figures compare the Baseline fuel and electricity mix scenario with a scenario in which the share of palm oil-based biodiesel in the diesel blend increases from 35% to 40% and with the Net-zero 2060 electricity mix scenario that reflects the Government of Indonesia's target of reaching net-zero emissions in the power sector by 2060.

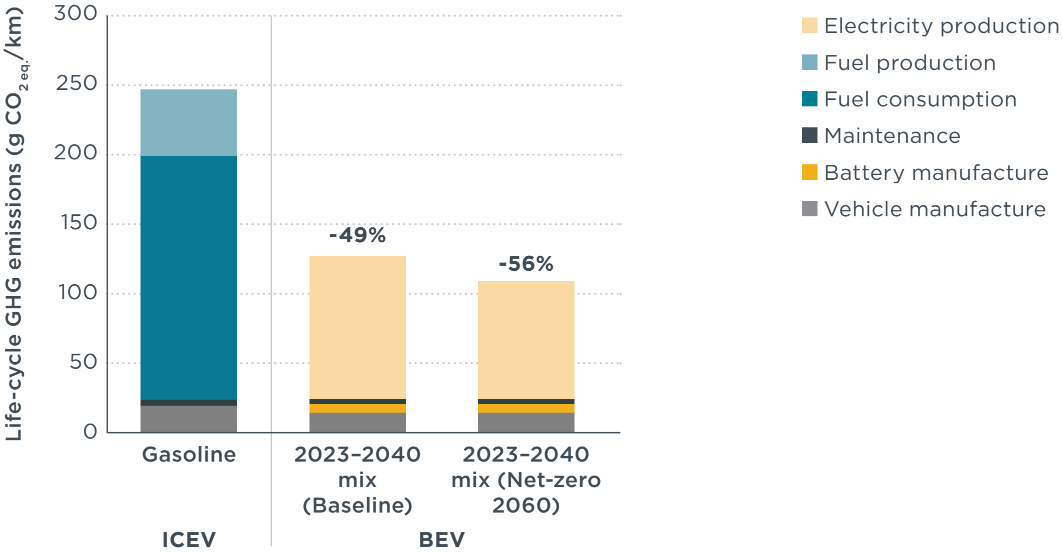



**Figure 5.** Life-cycle GHG emissions of A segment gasoline ICEVs and BEVs sold in Indonesia in 2023.

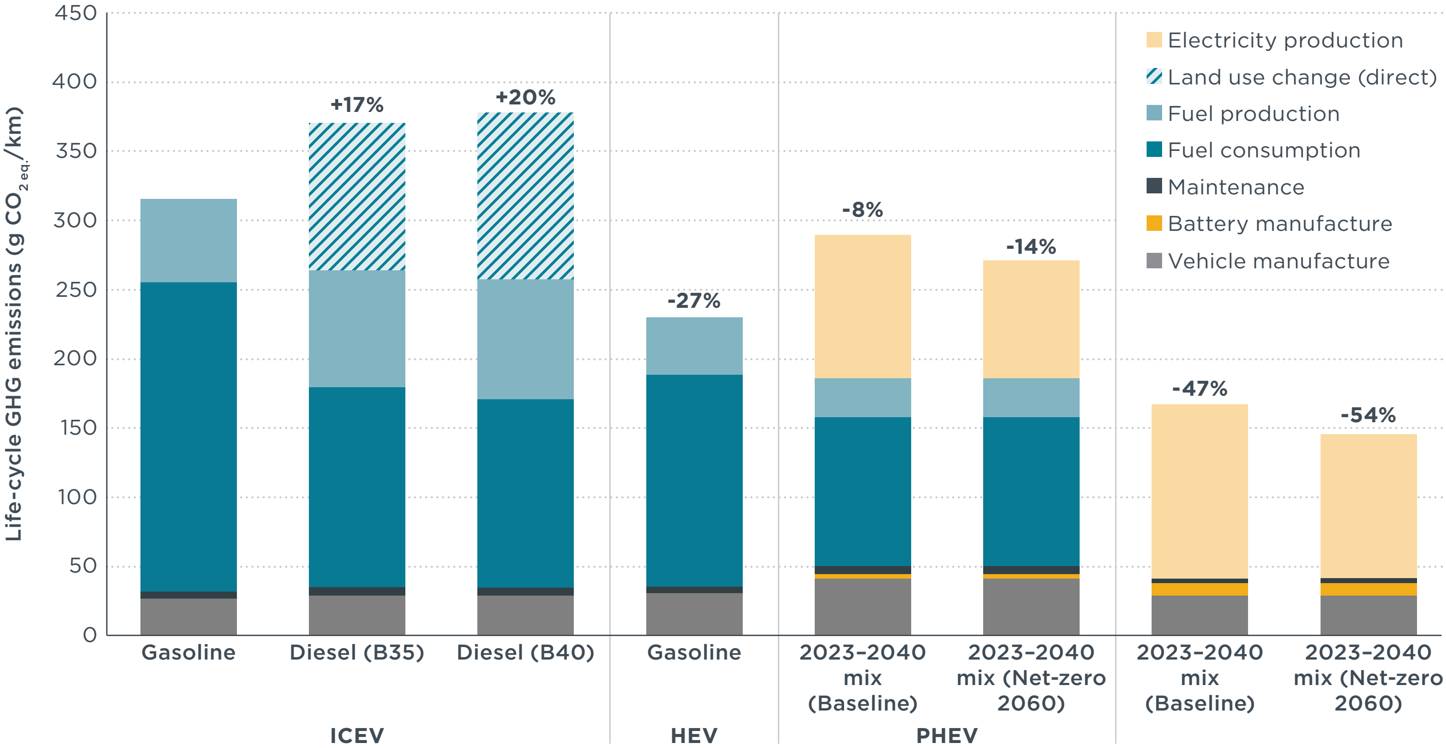



**Figure 6.** Life-cycle GHG emissions of SUV segment gasoline ICEVs, diesel ICEVs, HEVs, PHEVs, and BEVs sold in Indonesia in 2023.

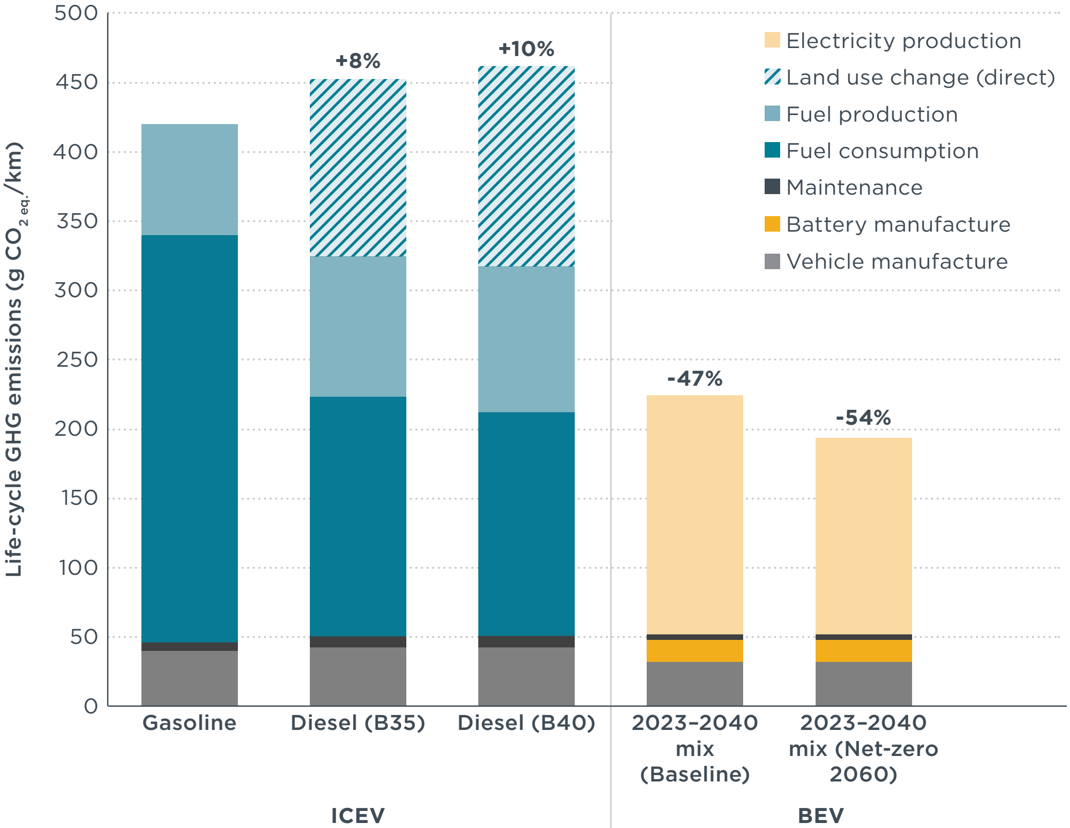



**Figure 7.** Life-cycle GHG emissions of MPV segment gasoline ICEVs, diesel ICEVs, and BEVs sold in Indonesia in 2023.

***Current BEVs correspond to 47%–56% lower life-cycle GHG emissions than gasoline cars.***
The life-cycle GHG emissions of gasoline ICEVs are estimated to be 246 g $CO_{2\ eq.}$/km for A segment cars, 316 g $CO_{2\ eq.}$/km for SUVs, and 420 g $CO_{2\ eq.}$/km for MPVs. The estimated life-cycle GHG emissions of the selected BEVs, in contrast, are 108–127 g $CO_{2\ eq.}$/km for A segment cars, 145–167 g $CO_{2\ eq.}$/km for SUVs, and 194–224 g $CO_{2\ eq.}$/km for MPVs. The higher values in these ranges correspond to future development of the grid mix under the Baseline scenario, and the lower values show the emissions under the Net-zero 2060 scenario. BEV emissions are 47%–49% lower than for comparable gasoline cars under the Baseline scenario and 54%–56% lower under the Net-zero 2060 scenario.

Emissions associated with BEV battery production are relatively small compared to total emissions. For A segment cars, SUVs, and MPVs, battery manufacturing corresponds to 6 g $CO_{2\ eq.}$/km, 9 g $CO_{2\ eq.}$/km, and 16 g $CO_{2\ eq.}$/km, respectively. If we assume a battery would need to be replaced once during a vehicle's lifetime, the life-cycle GHG emissions of BEVs increase by this amount to 115–133 g $CO_{2\ eq.}$/km for A segment cars, 154–176 g $CO_{2\ eq.}$/km for SUVs, and 210–241 g $CO_{2\ eq.}$/km for MPVs. Even in this case, the life-cycle GHG emissions of BEVs would be 44%–52% lower than gasoline cars under the Baseline scenario and 50%–53% lower under the Net-zero 2060 scenario.

***Hybrids have lower fuel consumption and lower GHG emissions than conventional cars.***
For the selected HEV model in the SUV segment, the real-world fuel consumption of 6.5 L/100 km is 32% lower than the 9.5 L/100 km for a comparable conventional gasoline car. This difference is relatively large when considering that for the average SUV segment HEVs in Europe, the average real-world fuel consumption is only 22% lower than for average conventional gasoline SUVs (Bieker, 2021a). When including the emissions of vehicle production and maintenance, the 32% lower fuel consumption translates into 27% lower life-cycle GHG emissions. In this study, SUV segment HEVs show life-cycle GHG emissions of 230 g $CO_{2\ eq.}$/km. Compared to BEVs, the emissions of HEVs are 37%–58% higher, depending on the future development of the electricity mix.

***In real-world operation, plug-in hybrids have a small climate benefit over conventional cars.***
The GHG emission benefits of PHEVs largely depend on the electric driving share in real-world operation and on the efficiency of the combustion engine and electric motor. Real-world evidence from more than 100,000 vehicles in Europe (Plötz et al., 2022), the United States (Isenstadt et al., 2022), and China (Plötz et al., 2020) shows that most PHEV models are driven more on fossil fuels than electricity.[3] In these regions, PHEVs show GHG emission benefits over conventional gasoline cars that are comparable to HEVs (Bieker, 2021a). However, due to the higher share of coal-based electricity in the average grid mix in Indonesia, the emission benefits of PHEVs are lower. In comparing the PHEV and conventional gasoline ICEV model in the SUV segment, this study shows the PHEV has 8% lower life-cycle GHG emissions under the Baseline scenario and 14% lower emissions under the Net-zero 2060 scenario. This is partly because the only PHEV model sold in Indonesia in the SUV segment is slightly larger than the models of the other power trains. Still, the emissions value of 271–290 g $CO_{2\ eq.}$/km is almost twice the value for BEVs in the SUV segment.

3 Official test cycles, such as the NEDC, WLTP, or the U.S. EPA's test cycles, tend to overestimate the electric driving share. Accordingly, real-world fuel consumption of private PHEVs in Europe, for instance, is found to be on average three times higher than considered in the WLTP numbers (Plötz et al., 2022). For PHEVs driven as company cars, fuel consumption is five times higher than in WLTP. The European Commission already reacted to this real-world gap and updated the electric driving share assumption for all PHEVs that will be type-approved from 2025 under Commission Regulation (EU) 2023/443 (European Commission, 2023).

***Diesel cars can have higher life-cycle GHG emissions than gasoline cars.***
For the current diesel blend B35, the life-cycle GHG emissions of diesel ICEVs correspond to 370 g $CO_{2\ eq.}$/km for SUV and 452 g $CO_{2\ eq.}$/km for MPV segment cars, which is 8%–17% higher than for gasoline ICEVs. If the biodiesel share were to increase to 40% (B40), the life-cycle emissions of diesel ICEVs would be even higher, at 378 g $CO_{2\ eq.}$/km for SUV and 461 g $CO_{2\ eq.}$/km for MPV segment cars. These values are 10%–20% higher than for gasoline ICEVs. The high emissions of diesel ICEVs are partly due to the DLUC emissions of biodiesel production. When not including DLUC emissions, the life-cycle GHG emissions are significantly lower, at 264 g $CO_{2\ eq.}$/km for SUVs and 325 g $CO_{2\ eq.}$/km for MPVs for the current biodiesel blend, and 258 g $CO_{2\ eq.}$/km and 317 g $CO_{2\ eq.}$/km for a 40% blend.

***Emissions during vehicle use are much higher than those during vehicle manufacturing.***
GHG emissions from the production and consumption of fuel and electricity correspond to 89%–91% of the life-cycle emissions of gasoline and diesel ICEVs, 81%–84% of the life-cycle emissions of HEVs and PHEVs, and 71%–81% of the life-cycle emissions of BEVs. The higher emissions of vehicle and battery manufacturing for the BEVs compared to their gasoline ICEV equivalents, which range from 7% higher emissions in the A segment to 41% higher emissions for SUVs, thus have a minor impact on overall GHG emissions. The largest GHG emissions mitigation potential comes from switching from ICEVs to BEVs, reducing the fuel consumption of ICEVs, and building renewable electricity capacities for charging BEVs with a cleaner grid mix.

## 2030 passenger cars

This section presents our estimates of the life-cycle GHG emissions over the lifetime of hypothetical passenger cars sold in 2030. As the average fuel consumption of passenger cars in Indonesia was constant in recent years (IEA, 2021), the fuel and electricity consumption of the future vehicle models is assumed to remain at the same level as today. The change in life-cycle GHG emissions compared to vehicles sold in 2023 thus mainly corresponds to differences in the fuel and electricity mix during the 2030 to 2047 lifetime. Figures 8, 9, and 10 present the life-cycle GHG emissions of future A segment passenger cars, SUVs, and MPVs, respectively.

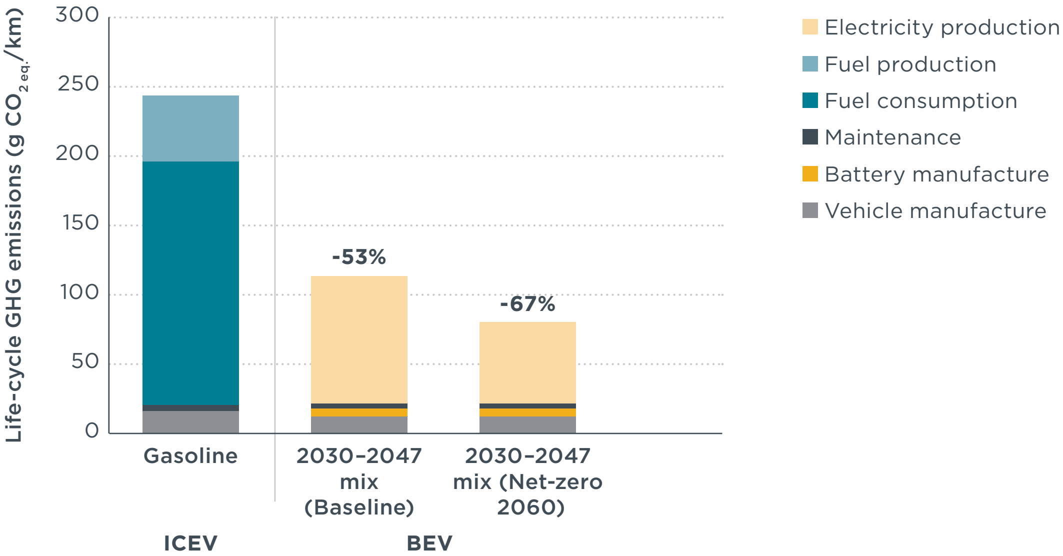



**Figure 8.** Life-cycle GHG emissions of A segment gasoline ICEVs and BEVs sold in Indonesia in 2030.

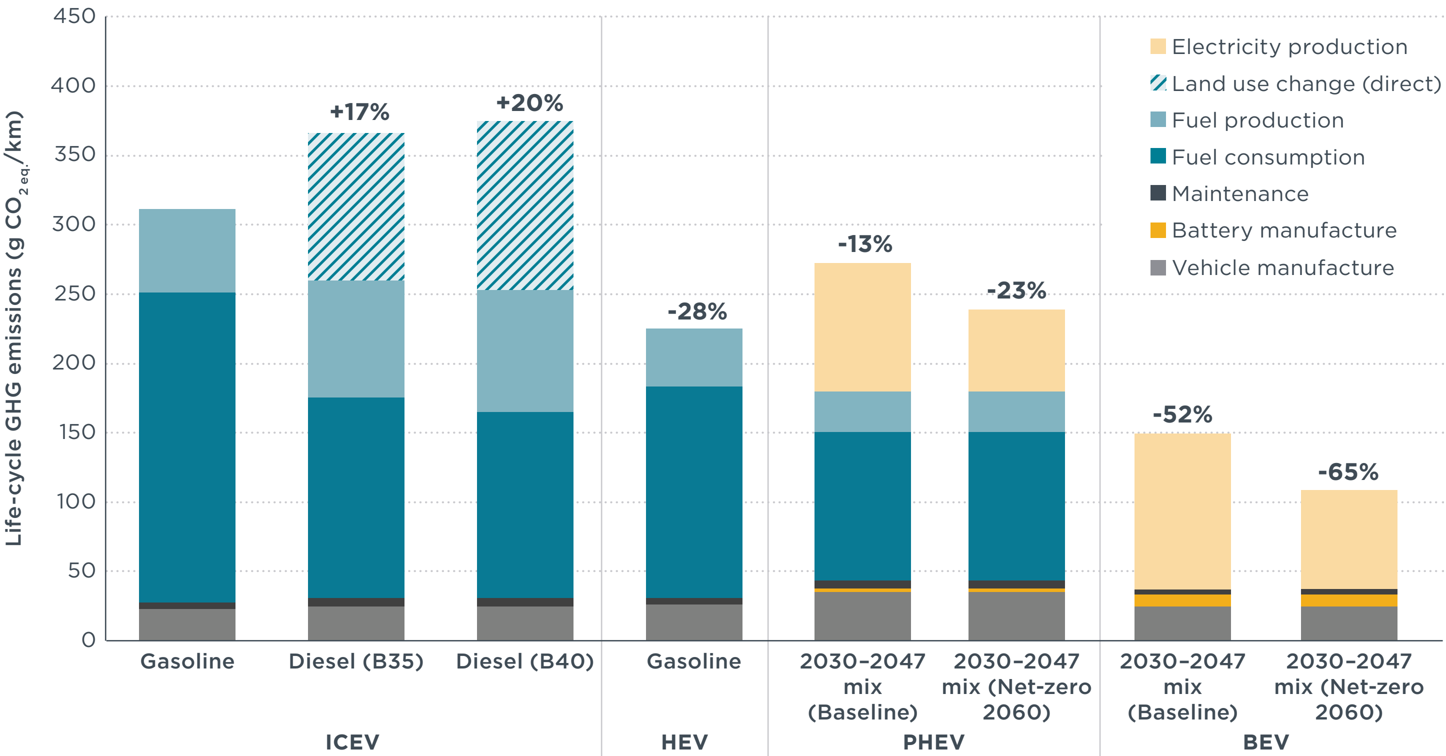



**Figure 9.** Life-cycle GHG emissions of SUV segment gasoline ICEVs, diesel ICEVs, HEVs, PHEVs, and BEVs sold in Indonesia in 2030.

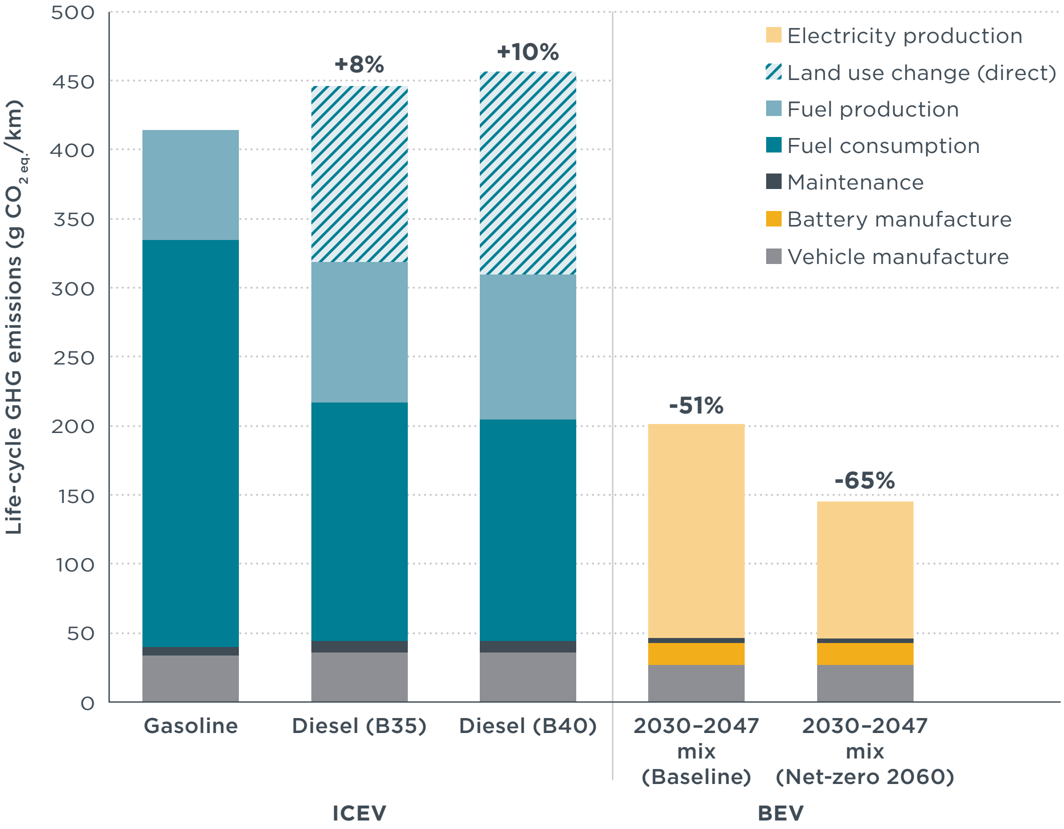



**Figure 10.** Life-cycle GHG emissions of MPV segment gasoline ICEVs, diesel ICEVs, and BEVs sold in Indonesia in 2030.

***The GHG emissions of 2030 ICEVs and HEVs are estimated to remain almost as high as today.***

Without improvement in vehicle fuel economy, the life-cycle GHG emissions of gasoline and diesel ICEVs and HEVs sold in Indonesia in 2030 are projected to remain almost as high as today. As vehicle production emissions are expected to decrease, the overall life-cycle GHG emissions would be only about 1%–2% lower than those for 2023 vehicles.

***With more renewables in the grid mix, the GHG emission benefits would increase for 2030 BEVs.***

Even though a 20% larger battery is considered for 2030 cars, the life-cycle GHG emissions of BEVs sold in 2030 are estimated to be 10%–26% lower than for BEVs sold in 2023. Depending on whether the Baseline or the Net-zero 2060 scenario for the development of the electricity mix is considered, their life-cycle GHG emissions correspond to 80–113 g $CO_{2\ eq.}$/km for A segment cars, 109–150 g $CO_{2\ eq.}$/km for SUVs, and 145–201 g $CO_{2\ eq.}$/km for MPVs. The selected BEVs sold in 2030 would thus correspond to 53%–67%, 52%–65%, and 51%–65% lower life-cycle GHG emissions, respectively, than comparable 2030 gasoline cars.

***Future PHEVs will drive on a cleaner grid, but still mainly rely on the combustion of fossil fuels.***

As PHEVs in average real-world operation run on fossil fuel for at least half of the kilometers driven, any decarbonization of the electricity mix reduces their emissions much less than for BEVs. The emissions value estimated here of 239–272 g $CO_{2\ eq.}$/km for an SUV segment PHEV sold in 2030 is 6%–12% lower than for a PHEV model sold in 2023. This is 13%–23% lower than estimated for a conventional gasoline car sold in 2030, and about twice as high as for BEVs.

### Hydrogen FCEVs

This section illustrates the life-cycle GHG emissions of FCEVs using different hydrogen pathways and compares the results with 2023 gasoline ICEVs and BEVs in the SUV segment. Figure 11 presents FCEVs driving on hydrogen produced from coal, natural gas, electrolysis using only renewable electricity, and electrolysis using the grid mix. The life-cycle GHG emissions of gasoline ICEVs and BEVs are also shown in Figure 11, for comparison, and this figure displays the life-cycle GHG emissions of BEVs when driving on the average grid mix and solely on renewable electricity. The GHG emissions corresponding to the production of the hydrogen system for FCEVs are distinguished from the emissions from producing the battery for BEVs and from the manufacturing of the rest of the vehicles.

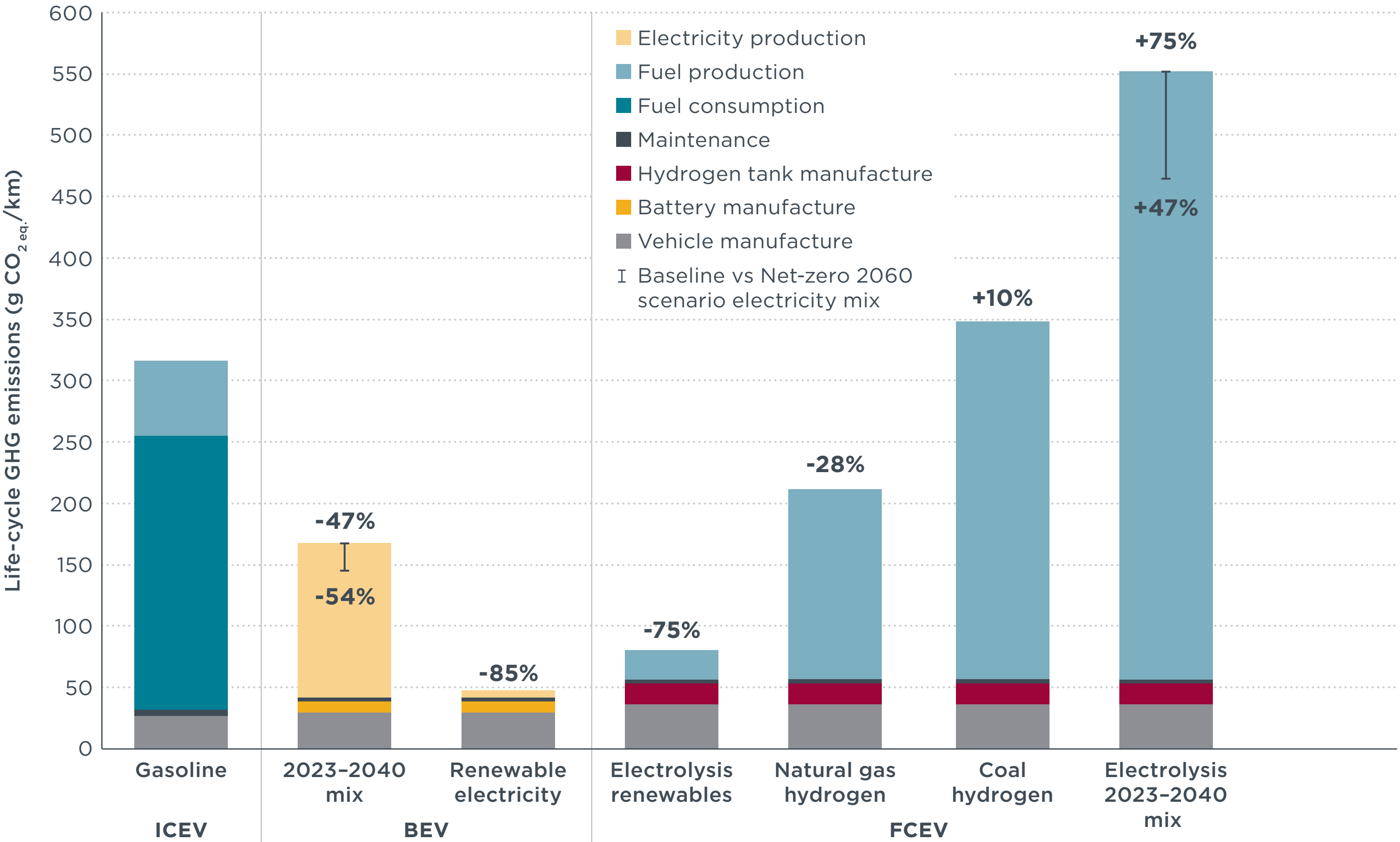



**Figure 11.** Life-cycle GHG emissions of SUV segment FCEVs using hydrogen from different production pathways compared with gasoline ICEVs and BEVs, all sold in Indonesia in 2023.

***Driving on green hydrogen corresponds to low GHG emissions, but using renewable electricity in BEVs leads to even lower emissions.***

When using hydrogen solely produced from additional renewable electricity supply, the life-cycle GHG emissions of FCEVs are estimated to be 80 g $CO_{2\ eq.}$/km, 75% lower than the emissions of a comparable gasoline ICEV. When directly using the renewable electricity to power BEVs, however, the life-cycle GHG emissions are even lower, 48 g $CO_{2\ eq.}$/km, and that is 85% lower than a comparable gasoline ICEV. The emissions when using green hydrogen are higher than using renewable electricity in BEVs because the process of electrolysis, hydrogen compression, conversion of hydrogen back to electricity in the fuel cell, and eventually using that electricity in a motor to propel an FCEV is three times more energy intensive than using the electricity to charge a battery and directly power an electric motor in a BEV (Bieker, 2021a).

***Hydrogen made from grid electricity leads to the highest GHG emissions.*** While producing hydrogen from renewable electricity corresponds to low GHG emissions, using the grid mix would result in the highest GHG emissions of all power train types and fuel pathways assessed in this study. Under the Baseline scenario, the life-cycle GHG emissions of an FCEV would be as high as 552 g $CO_{2\ eq.}$/km, and under the Net-zero 2060 scenario, they are estimated at 465 g $CO_{2\ eq.}$/km. These emission levels are 75% (Baseline) and 47% (Net-zero 2060) higher than those of gasoline ICEVs.

***Natural gas-based hydrogen offers only a small benefit over gasoline cars.*** Using hydrogen produced from natural gas via steam reforming, the life-cycle emissions of an FCEV are estimated to be 212 g $CO_{2\ eq.}$/km, 28% lower than for gasoline ICEVs and 26% higher than those of today's BEVs charged with the Baseline electricity mix.

***Coal-based hydrogen leads to higher emissions than gasoline cars.*** Coal-based hydrogen has high life-cycle GHG emissions because of the $CO_2$ and methane emissions of coal extraction, processing, and transport, and the process of coal gasification. The life-cycle GHG emissions of FCEVs driving on coal-based hydrogen are estimated to be 348 g $CO_{2\ eq.}$/km, 10% higher than those of gasoline ICEVs.

## TWO-WHEELERS

Figure 12 shows the life-cycle GHG emissions (in g $CO_{2\ eq.}$/km) for the selected gasoline-powered and electric scooters when considering a 12-year lifetime from 2023 to 2034. Figure 13 shows the life-cycle GHG emissions of gasoline-powered and electric scooters used from 2030 to 2041. As no fuel economy policy is in place, the fuel and electricity consumption of future models is assumed to remain the same as for today's models, and Figure 13 thus mainly reflects the changes in the fuel and electricity mix.

As in the previous sections, the figure displays the GHG emissions corresponding to the vehicle cycle, including the manufacturing of the battery for the BEV and the rest of the vehicle, and the emissions corresponding to maintenance, fuel and electricity production, and fuel consumption. For the development of the electricity mix, the Baseline scenario is compared to the Net-zero 2060 scenario, which reflects the Government of Indonesia's target of reaching net-zero emissions by 2060.

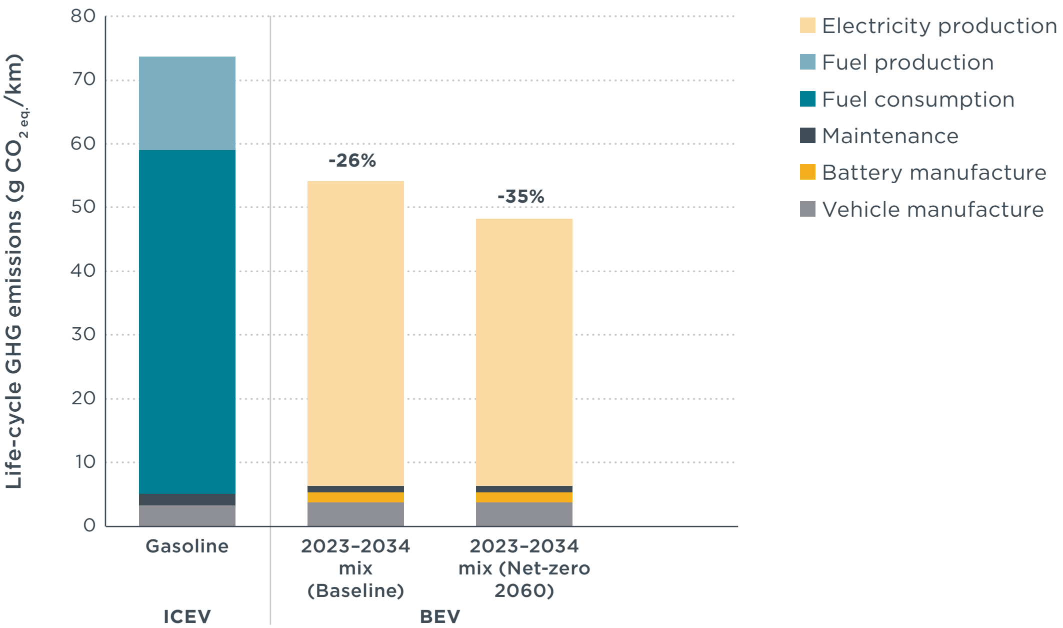



**Figure 12.** Life-cycle GHG emissions of gasoline-powered and electric scooters sold in Indonesia in 2023.

***Today's electric scooters correspond to 26%–35% lower life-cycle GHG emissions than gasoline scooters.***

The life-cycle GHG emissions from the gasoline-powered scooter are estimated to be 74 g $CO_{2\ eq.}$/km and those of the electric scooter are estimated to be 48–54 g $CO_{2\ eq.}$/km, depending on whether the Baseline scenario (higher value) or the Net-zero 2060 scenario is considered for the development of the electricity mix. The electric scooter thereby corresponds to 26%–35% lower life-cycle GHG emissions than the gasoline model.

The GHG emissions impact of battery production for electric scooters is a relatively small 2 g $CO_{2\ eq.}$/km. If we assume a battery would need to be replaced during a vehicle's lifetime, the life-cycle GHG emissions of the electric scooter increase to 50–56 g $CO_{2\ eq.}$/km, depending on the development of the electricity mix. These values are still 24%–32% lower than for the comparable gasoline model.

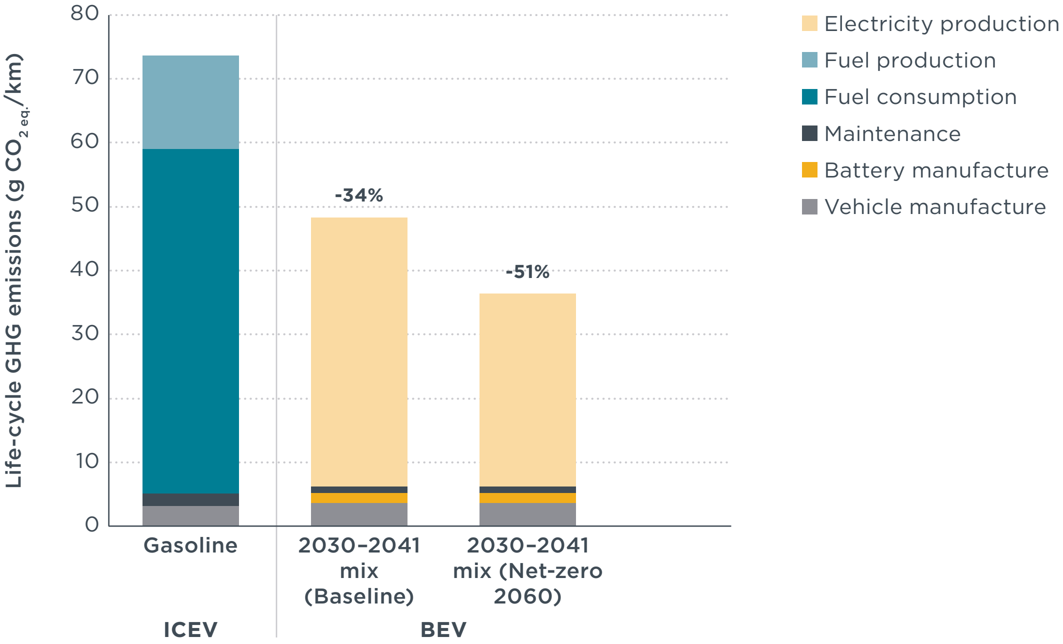



**Figure 13.** Life-cycle GHG emissions of gasoline-powered and electric scooters sold in Indonesia in 2030.

***The GHG emission benefit would increase for electric scooters sold in 2030.***
While gasoline scooters sold in 2030 show practically the same life-cycle GHG emissions as those sold in 2023, the emissions of 2030 electric scooters would decrease to 48 g $CO_{2\ eq.}$/km for the Baseline and to 36 g $CO_{2\ eq.}$/km for the Net-zero 2060 electricity mix scenarios. For vehicles sold in 2030, electric scooters would thus show 34%–51% lower emissions than gasoline scooters.

***Scooters powered by renewable electricity correspond to 89% lower emissions than gasoline models.***
If powered only by renewable electricity, the life-cycle GHG emissions of 2030 electric scooters would be 8 g $CO_{2\ eq.}$/km, 89% lower than 2023 or 2030 gasoline scooters.

## SUMMARY

Figure 14 summarizes the findings for gasoline ICEVs and BEVs across the three passenger car segments and for scooters and shows that BEVs sold in both 2023 and 2030 are associated with significantly lower life-cycle GHG emissions. This study also assessed diesel ICEVs, HEVs, and PHEVs in the SUV segment; BEVs similarly showed significantly lower GHG emissions. With the continuous decarbonization of the electricity grid in Indonesia that is expected in coming decades, the GHG emissions performance of electric passenger cars and two-wheelers will improve and align with the Government's climate targets. Similarly strong performance is only possible from FCEVs if the hydrogen used to power vehicles is solely produced from additional renewable electricity; using coal-based hydrogen or hydrogen produced from the average electricity mix, in contrast, would increase emissions compared to gasoline vehicles. Note, too, that driving on electricity-based hydrogen consumes about three times more energy than directly using electricity to power BEVs.

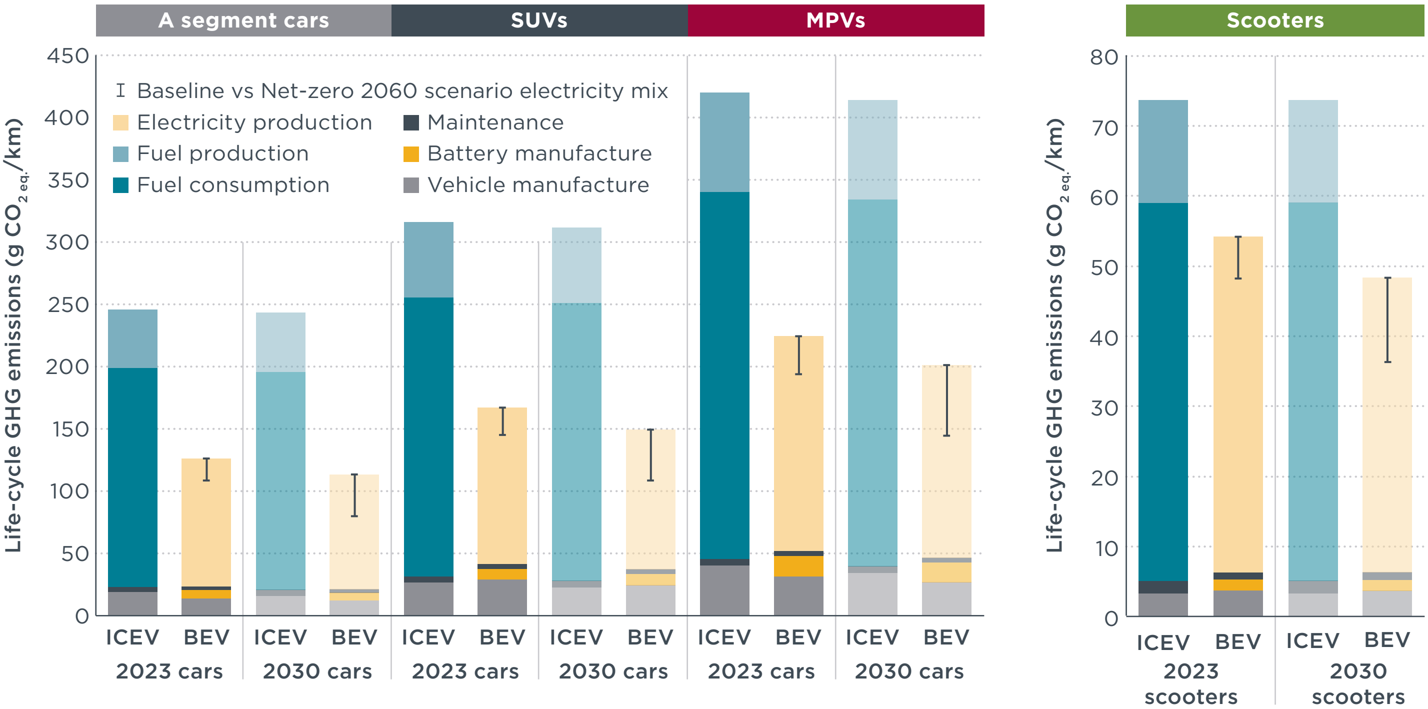



**Figure 14.** Life-cycle GHG emissions of A segment, SUV segment, and MPV segment gasoline ICEVs and BEVs, as well as electric and combustion engine scooters sold in Indonesia in 2023 and in 2030. The error bars indicate differences between the development of the electricity mix according to a current policy Baseline scenario (higher values) and a development in line with the Government's target of reaching net-zero emissions by 2060.

### BEVs

In the Baseline scenario for the development of the electricity mix over the lifetime of vehicles sold in 2023, electric passenger cars correspond to 47%–49% lower emissions than their gasoline counterparts, depending on the segment. Under the Net-zero 2060 scenario for the grid, the GHG emissions of BEVs sold in 2023 are 54%–56% lower than for gasoline cars. Emissions from battery production are a relatively small portion of total life-cycle GHG emissions. Even when assuming a battery would need to be replaced during a vehicle's lifetime, BEVs show 44%–52% lower emissions in the Baseline scenario, depending on the segment, and 50%–53% lower emissions in the Net-zero 2060 scenario. For hypothetical vehicles sold in 2030, BEVs would offer an even larger life-cycle GHG emission benefit, 51%–53% lower emissions than for gasoline cars depending on the segment in the Baseline scenario, and 65%–67% under the

Net-zero 2060 electricity mix. Once fully powered by renewable electricity, BEVs would correspond to 85%–89% lower emissions than gasoline cars.

### Electric scooters

The findings for electric scooters are similar to those for passenger cars. Already with the Baseline scenario for the electricity mix, today's electric scooters correspond to 26% lower life-cycle GHG emissions of their representative gasoline counterpart, while the Net-zero 2060 scenario indicates a GHG emission benefit of 35%. When assuming that a battery replacement would be required, the emission benefit is at 24% for the Baseline and 32% for the Net-zero 2060 scenario. Comparing the two-wheelers projected to be sold in 2030, the reduction of GHG emissions is estimated at 34% for the Baseline and 51% for the Net-zero 2060 scenario. Also here, when powered by renewable electricity only, the GHG emissions of electric scooters would be 89% lower than those of gasoline models.

### HEVs

For passenger cars, the study finds that HEVs offer a smaller reduction in life-cycle GHG emissions than BEVs. Because the vehicles consume less fuel than conventional gasoline cars, HEVs offer a 27% reduction in emissions compared to gasoline cars. This reduction is considered to be at the upper end of the expected benefit of HEVs over conventional ICEVs globally, as the difference in fuel consumption between the HEV and ICEV model in this study is larger than for average SUV segment HEVs and ICEVs in Europe, for instance. Still, the GHG emission benefits of HEVs in Indonesia is only about half that of battery electric cars in the same segment, even if only the Baseline electricity mix scenario is considered. If the electricity mix develops in line with the Net-zero 2060 scenario, HEVs show an even smaller portion of the emission reduction that can be achieved with BEVs. In contrast to BEVs, HEVs do not offer a reduction in GHG emissions that can approach zero emissions.

### PHEVs

The GHG emissions of PHEVs largely depend on the electric driving share in real-world operation. Large-scale evidence from more than 100,000 vehicles in Europe, the United States, and China shows that most PHEV models are driven more on fossil fuels than electricity. In these regions, the life-cycle GHG emissions of PHEVs are comparable to HEVs. With a higher share of coal-based electricity in the average grid mix in Indonesia, however, the emission benefit of PHEVs is lower. Indeed, as assessed in the SUV segment in this study, PHEVs show 8%–14% lower life-cycle GHG emissions than conventional gasoline ICEVs, depending on the future development of the electricity mix. This comparatively low emission benefit is also because the only PHEV model in the SUV segment sold in Indonesia is slightly larger than the models selected for the other power train types. Still, the emissions value of that model is twice as high as for BEVs in the SUV segment. For future vehicles, the GHG emission benefits of PHEVs compared with gasoline cars does not grow as much as for BEVs, as PHEVs in average real-world operation still largely rely on the combustion of fossil fuels. For this reason, unlike BEVs, this power train type cannot approach zero emissions once the electricity mix is largely based on renewables.

### Diesel ICEVs

The climate impact of diesel ICEVs in Indonesia differs with the scope of emissions included. When not including the climate impact of expanding the agricultural area for biodiesel production, diesel cars have lower GHG emissions than gasoline cars: 19%–29% lower for a 35% blend (B35), depending on the segment, and 22%–32% lower when increasing the share of biodiesel to 40% (B40). When including DLUC emissions, in contrast, the full climate impact of diesel cars is higher than for gasoline cars. For the current 35% biodiesel blend, the life-cycle GHG emissions of diesel SUVs and MPVs are 8% and 17% higher, respectively, than for comparable gasoline models. With a higher biodiesel share of 40%, the life-cycle climate impact of diesel ICEVs would increase further, to a level 10%–20% higher than for gasoline cars, depending on the segment. Even when not considering DLUC emissions, diesel ICEVs have significantly higher life-cycle GHG emissions than BEVs and cannot approach zero GHG emissions in the future.

### Hydrogen FCEVs

The life-cycle GHG emissions of hydrogen FCEVs largely vary by hydrogen production pathway. For natural gas-based hydrogen, the life-cycle GHG emissions of driving an FCEV are 33% lower than for a comparable gasoline vehicle. Driving with coal-based hydrogen, in contrast, shows 10% higher emissions that gasoline ICEVs. With electricity-based hydrogen produced from the average electricity mix, GHG emissions are 75% higher than gasoline cars. When compared with BEVs powered with the same average electricity mix, the life-cycle GHG emissions of FCEVs are three times higher. This is due to the high energy losses of producing hydrogen via electrolysis and converting it back to electricity instead of directly using the electricity to charge a BEV. As presented by Bieker (2021a), the energy demand of driving on electricity-based hydrogen is three times higher than the energy demand of BEVs. When using only renewable electricity to produce hydrogen, the difference between the GHG emissions of FCEVs and BEVs diminishes; here, FCEVs show 75% lower emissions than gasoline ICEVs, similar to the 85% reduction of renewable electricity-powered BEVs. FCEVs thus only have one low-carbon pathway: hydrogen produced from additional renewable electricity. While the GHG emission benefit of FCEVs over gasoline cars is limited when using natural gas-based hydrogen, using coal-based hydrogen and average electricity-based hydrogen would increase GHG emissions.

# DISCUSSION

Conventional gasoline ICEVs, diesel ICEVs, HEVs, and PHEVs rely on the combustion of fossil fuels, even though they are partially blended with biofuels. Further, the use of biofuels does not necessarily offer a large emission benefit when compared with using fossil fuels (Searle, 2019). Conventional combustion engine vehicles, HEVs, and PHEVs thus do not allow for the deep emission reductions needed for Indonesia to approach zero emissions from transport in the longer term. The vehicle lifetime of 18 years or more is important to remember when considering strategies to support economy-wide net-zero emissions by 2060. If the on-road stock of passenger cars and two-wheelers in Indonesia is to be close to 100% BEVs and FCEVs by that year, sales of new ICEVs, HEVs, and PHEVs would need to be phased out by around 2040.

This analysis reflects the same trends observed in previous ICCT analyses of vehicles in China, Europe, India, and the United States (Bieker, 2021a; Bieker, 2021b). In all of these markets, BEVs are found to correspond to the lowest life-cycle GHG emissions of all assessed power trains already for vehicles sold today. For future vehicles, the emission benefits are expected to increase alongside the continuous decarbonization of the electricity mix.

This study is based on the characteristics of the most popular gasoline ICEV models and comparable BEVs, and, where applicable, also diesel ICEVs, HEVs, PHEVs, and FCEVs. There are limitations to this approach. For one, performing an LCA that uses the segment-average fuel and electricity consumption of the respective power train types would better represent the Indonesian fleet. As the fuel consumption of the gasoline ICEV models used in this study is generally lower than the 2019 average fuel consumption of gasoline vehicles in the respective segments in Indonesia (IEA, 2021), this study likely underestimates the life-cycle GHG emissions of gasoline cars in Indonesia. This means that it also likely underestimates the GHG emission benefit of BEVs.

For future vehicles, this study assumes the same fuel and electricity consumption as observed for today's vehicle models. Things like reducing vehicle weight, high-efficiency engine designs, engine downsizing with turbocharging, and improved aerodynamics could improve the fuel consumption of future gasoline ICEVs, diesel ICEVs, and HEVs. Most of these approaches are currently not present in Indonesia's fleet, as reflected in the higher fuel consumption in Indonesia than in major markets and similar countries (Mahalana & Yang, 2021). Indeed, the average fuel consumption of new vehicles in Indonesia has remained relatively constant in recent years (IEA, 2021).

The electrification of transport will increase electricity demand in Indonesia and require additional electricity-generation capacity. This increase in demand is accounted for in the Baseline and Net-zero 2060 electricity mix scenarios. In the Baseline scenario, the underlying Rencana Usaha Penyediaan Tenaga Listrik, the National Electricity Supply Business Plan, considers the total electricity production to increase from 290 TWh in 2021 to 445 TWh in 2030 (Government of Indonesia and PLN, 2021), and in the Net-zero 2060 scenario, the electricity production is considered to increase to 507 TWh in 2030 (IEA, 2022a). This production is considered to increase further to 1,600 TWh of electricity production in 2060. For the future electricity demand from electric vehicles in Indonesia, the Net-zero 2060 scenario includes a share of electric vehicles in the passenger car stock of 8% in 2030 and 90% in 2060. In the two- and three-wheelers vehicle stock, an electric vehicle share of 20% in 2030 and 100% in 2060 is considered (IEA, 2022a).

# POLICY IMPLICATIONS

Having shown that battery electric passenger cars and electric scooters are associated with lower life-cycle GHG emissions than gasoline ICEVs, diesel ICEVs, HEVs, and PHEVs already for vehicles produced today, this section explores policy options that emerge for Indonesia. Beyond GHG emissions, increasing the share of electric vehicles in the on-road fleet will yield co-benefits that include mitigating the public health and environmental consequences of air pollution in Indonesian cities, reducing Indonesia's dependence on oil imports, and reducing public spending on fuel subsidies. Additionally, as Indonesia is the world's largest supplier of nickel and has rich reserves of other key battery materials, including cobalt, manganese, copper, and aluminium, creating a domestic battery and electric vehicle manufacturing industry is expected to create jobs and grow the economy.

Given our findings, policymakers in Indonesia could consider the following options:

**Specific policy supports would help spur domestic battery and electric vehicle production in Indonesia.** Based on international experience, government actions such as setting targets for electric vehicle production, exports, and national sales shares, and providing administrative and financial support for mineral mining and processing are important for developing domestic battery and electric vehicle supply chains. The Ministry of Industry's electric vehicle production and sales share targets, and the current tax deduction for electric vehicle manufacturers are first steps to help establish Indonesia's place in the global electric vehicle production and supply chain, but more policy support would help ensure the targets are achieved.

**Phasing out sales of new combustion engine cars and two-wheelers by around 2040 would help align the transport sector with Indonesia's 2060 net-zero emissions target.** A fully electric passenger car and two-wheeler fleet combined with a largely renewable electric grid would allow these fleets to approach zero emissions. Both goals would need to be pursued in parallel. Because passenger cars have an average vehicle lifetime of 18 to 20 years, a fully electric fleet in 2060 requires that starting in around 2040, no new combustion engine cars or hybrids are sold in Indonesia. Electric two-wheelers, meanwhile, are expected to be cheaper in terms of total cost of ownership than combustion engine models soon (Asian Development Bank, 2022); sales of new ICEVs in this segment could be phased out sooner than 2040 to achieve earlier GHG emission savings.

**Electric vehicle sales mandates and/or corporate average fuel economy standards for passenger cars and two-wheelers help manufacturers to continuously increase the share of BEV in their fleets.** Experiences in China, the European Union, and other markets show that an increase in BEV sales can be achieved by the introduction of corporate average fuel economy standards in combination with purchase subsidies and tax incentives for electric vehicles. In the short term, corporate average fuel economy standards would reduce the fuel consumption and emissions of combustion engine cars, including a shift from conventional ICEVs to more fuel-efficient HEVs. By increasing the stringency in the longer term, they guide manufacturers to increase the BEV share, and thereby prepare a future phaseout of sales of new ICEVs, HEVs, and PHEVs. Indonesia could consider such standards for both passenger cars and two-wheelers. Alternatively, as experiences in California and other U.S. states show, electric vehicle sales share mandates can target an increase in BEV sales more directly. The Government of Indonesia could further support the development of the domestic battery and BEV industry by purchasing domestically produced BEVs for public vehicle fleets.

**Public spending on purchase subsidies and tax incentives for BEVs could be balanced by higher taxes on high-polluting vehicles.** Prior ICCT research showed that a BEV in Indonesia costs more to purchase than a comparable combustion engine car (Mahalana et al., 2023). This higher purchase cost is amplified by tax rates for the value-added tax, transfer tax, and circulation tax, all of which are based on vehicle purchase price. Although BEV production costs are expected to continuously decrease in future years, it is important to bridge this cost gap in Indonesia in the short term; the current purchase subsidies, value-added tax reductions, and luxury tax reductions for electric passenger cars and two-wheelers are important steps in this direction. To balance the public expenditures on BEV incentives, the Government could introduce a revenue-neutral feebate program in which such incentives are compensated for by higher taxes on highly polluting vehicles. This type of feebate program has been introduced successfully in France, Thailand, and Singapore.

**Providing non-financial benefits for BEV users increases the attractiveness of driving a BEV.** In parallel with fiscal incentives, the Government of Indonesia and regional and city governments could explore non-financial benefits for BEVs such as the creation of low- or zero-emission zones in cities, road-access privileges, and dedicated parking spaces. For example, Jakarta has started to develop municipal parking systems that allow BEV users to receive the lowest parking fare and access to dedicated parking spaces. BEV users could further be granted preferential access to road infrastructure. Here Jakarta is also an example, as BEVs do not fall under the odd-even number plate driving restrictions in the city.

**Supporting the deployment of home, workplace, and public charging points would be expected to facilitate BEV adoption and create new jobs.** While PLN is tasked with developing a national framework for electric vehicle charging infrastructure, collaboration with local governments and the private sector is needed to overcome administrative and financial challenges in the deployment of charging infrastructure. The Government could encourage private investment in charging infrastructure, for instance through tax incentives. Building out public and private charging infrastructure provides a large opportunity to create new jobs.

# REFERENCES


Agora Verkehrswende. (2019). *Klimabilanz von strombasierten Antrieben und Kraftstoffen* [Life-cycle assessment of electricity-based power trains and fuels.] https://www.agora-verkehrswende.de/fileadmin/Projekte/2019/Klimabilanz_Batteriefahrzeugen/82_Klimabilanz_E-Autos_alt-Antriebe-V2.pdf

Allgemeiner Deutscher Automobil-Club. (2021, May). *ADAC Ecotest*. https://www.adac.de/rund-ums-fahrzeug/tests/ecotest/

Anup, S., Deo, A., & Bandivadekar, A. (2021). *Fuel consumption reduction technologies for the two-wheeler fleet in India*. International Council on Clean Transportation. https://theicct.org/publication/fuel-consumption-reduction-technologies-for-the-two-wheeler-fleet-in-india/

Argonne National Laboratory. (2020). *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)* (Version 2020). https://greet.es.anl.gov/index.php

Argonne National Laboratory. (2022). *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)* (Version 2022). https://greet.es.anl.gov/index.php

Asian Development Bank. (2022). *Electric Motorcycle Charging Infrastructure Road Map for Indonesia.* Asia Development Bank. https://www.adb.org/publications/electric-motorcycle-charging-infrastructure-indonesia

Austin, K. G., Mosnier, A., Pirker, J., McCallum, I., Fritz, S., & Kasibhatla, P. S. (2017). Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land Use Policy*, *69*, 41–48. https://doi.org/10.1016/j.landusepol.2017.08.036

Bieker, G. (2021a). *A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars*. International Council on Clean Transportation. https://theicct.org/publications/global-LCA-passenger-cars-jul2021

Bieker, G. (2021b). *Life-cycle greenhouse gas emissions of combustion engine and electric passenger cars and two-wheelers in India*. International Council on Clean Transportation. https://theicct.org/publication/life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars-and-two-wheelers-in-india/

Carranza, G., Do Nascimiento, M., Fanals, J., Febrer, J., & Valderrama, C. (2022). Life cycle assessment and economic analysis of the electric motorcycle in the city of Barcelona and the impact on air pollution. *Science of The Total Environment*, *821*, 153419. https://doi.org/10.1016/j.scitotenv.2022.153419

Christensen, A., & Petrenko, C. (2017). *$CO_2$-based synthetic fuel: Assessment of potential European capacity and environmental performance*. International Council on Clean Transportation. https://theicct.org/publication/co2-based-synthetic-fuel-assessment-of-potential-european-capacity-and-environmental-performance/

Council of the European Union. (2015). Council Directive (EU) 2015/652 of 20 April 2015 laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels. *Official Journal of the European Union*, *L107*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L0652&from=DE

Cox, B. L., & Mutel, C. L. (2018). The environmental and cost performance of current and future motorcycles. *Applied Energy*, *212*, 1013–1024. https://doi.org/10.1016/j.apenergy.2017.12.100

Deendarlianto, Widyaparaga, A., Widodo, T., Handika, I., Chandra Setiawan, I., & Lindasista, A. (2020). Modelling of Indonesian road transport energy sector in order to fulfill the national energy and oil reduction targets. *Renewable Energy*, *146*, 504–518. https://doi.org/10.1016/j.renene.2019.06.169

Dornoff, J., Tietge, U., & Mock, P. (2020). *On the way to "real-world" $CO_2$ values: The European passenger car market in its first year after introducing the WLTP*. International Council on Clean Transportation. https://theicct.org/publication/on-the-way-to-real-world-co2-values-the-european-passenger-car-market-in-its-first-year-after-introducing-the-wltp/

European Commission. (2023). *Commission Regulation (EU) 2023/443 of 8 February 2023 amending Regulation (EU) 2017/1151 as regards the emission type approval procedures for light passenger and commercial vehicles*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R0443

EV-volumes. (2022). *EV Data Center*. https://www.ev-volumes.com/datacenter/

Food and Agriculture Organization of the United Nations. (2008). *Harmonized world soil database v1.2 | FAO soils portal* [Data set]. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

Food and Agriculture Organization of the United Nations. (2023). *FAOSTAT. Crops and livestock products*. https://www.fao.org/faostat/en/#data/QCL

Fuelly. (2022, July). *Fuelly track, share, and compare your vehicle*. https://www.fuelly.com

Fraunhofer Institute for Systems and Innovation Research ISI. (2019). *Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw* [Climate impact, costs, and potential of different fuels and powertrain types for cars and trucks]. Fraunhofer ISI. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2019/klimabilanz-kosten-potenziale-antriebe-pkw-lkw.pdf

Gabungan Industri Kendaraan Bermotor Indonesia. (2023a). *Indonesian Automobile Industry Data*. https://www.gaikindo.or.id/

Gabungan Industri Kendaraan Bermotor Indonesia. (2023b). *Wuling Siapkan Strategi Hadapi Perekonomian Global 2023* [Wuling Prepares Strategies to Face the 2023 Global Economy]. https://www.gaikindo.or.id/wuling-siapkan-strategi-hadapi-perekonomian-global-2023/

Ge, M., Friedrich, J., & Vigna, L. (2022). *4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors*. World Resources Institute. https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Government of Indonesia. (2014). *Peraturan Pemerintah (PP) Nomor 79 Tahun 2014 tentang Kebijakan Energi Nasional* [Government Regulation Number 79 of 2014 concerning National Energy Policy]. https://peraturan.bpk.go.id/Home/Details/5523/pp-no-79-tahun-2014

Government of Indonesia. (2021). *Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Indonesia LTS-LCCR 2050)*. https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf

Government of Indonesia. (2022). *Enhanced National Determined Contribution Indonesia*. https://unfccc.int/sites/default/files/NDC/2022-09/23.09.2022_Enhanced%20NDC%20Indonesia.pdf

Government of Indonesia and Perusahaan Listrik Negara. (2021). *Rencana Usaha Penyediaan Tenaga Listrikc (RUPTL) 2021-2030* [Electricity supply business plan (RUPTL) 2021-2030]. https://web.pln.co.id/statics/uploads/2021/10/ruptl-2021-2030.pdf

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta analysis. *Global Change Biology*, *8*(4), 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Harlow, J. E., Ma, X., Li, J., Logan, E., Liu, Y., Zhang, N., Ma, L., Glazier, S. L., Cormier, M. M. E., Genovese, M., Buteau, S., Cameron, A., Stark, J. E., & Dahn, J. R. (2019). A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies. *Journal of The Electrochemical Society*, *166*(13), A3031. https://doi.org/10.1149/2.0981913jes

Heidt, C., Jamet, M., Räder, D., & Weber, T. (2019). *Greenhouse Gas Emissions of Transport and Reduction Potentials of BRT in Bandung, Pekanbaru and Semarang.* Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). https://www.changing-transport.org/wp-content/uploads/2020_GHG-of-Transport-and-Reduction-Potentials-of-BRT-in-Bandung-Pekanbaru-and-Semarang.pdf

Hill, N., Amaral, S., Morgan-Price, S., Nokes, T., Bates, J., Helms, H., Fehrenbach, H., Biemann, K., Abdalla, N., Jöhrens, J., Cotton, E., German, L., Harris, A., Haye, S., Sim, C., & Bauen, A. (2020). *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*. Ricardo-AEA, ifeu, E4tech. https://data.europa.eu/doi/10.2834/91418

Intergovernmental Panel on Climate Change. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds.)]. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html

Intergovernmental Panel on Climate Change. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg1/

International Council on Clean Transportation. (2020). *Vision 2050: A strategy to decarbonize the global transport sector by mid-century*. https://theicct.org/publication/vision-2050-a-strategy-to-decarbonize-the-global-transport-sector-by-mid-century/

International Energy Agency. (2021). *Fuel economy in Indonesia*. https://www.iea.org/articles/fuel-economy-in-indonesia

International Energy Agency. (2022a). *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*. https://www.iea.org/reports/an-energy-sector-roadmap-to-net-zero-emissions-in-indonesia

International Energy Agency. (2022b). *Global Hydrogen Review 2022*. https://www.iea.org/reports/global-hydrogen-review-2022

Isenstadt, A., Yang, Z., Searle, S., & German, J. (2022). *Real world usage of plug-in hybrid vehicles in the United States*. https://theicct.org/publication/real-world-phev-us-dec22/

Le, H., & Yang, Z. (2022). *Market analysis of two- and three-wheeler vehicles in key ASEAN member states*. International Council on Clean Transportation. https://theicct.org/publication/asia-pacific-lvs-ndc-tia-23w-market-asean-countries-jun22/

Mahalana, A., & Yang, Z. (2021). *Overview of vehicle fuel efficiency and electrification policies in Indonesia*. International Council on Clean Transportation. https://theicct.org/publication/overview-of-vehicle-fuel-efficiency-and-electrification-policies-in-indonesia/

Mahalana, A., Yang, Z., & Posada, F. (2023). *The consumer cost of ownership of electric passenger cars in Indonesia*. International Council on Clean Transportation. https://theicct.org/publication/asia-pacific-evs-cco-evs-indonesia-jan23/

MarkLines. (2022, July). *Automobil industry portal MarkLines*. https://www.marklines.com/

Ministry of Energy and Mineral Resources. (2022). *Handbook of energy and economic statistics of Indonesia 2021*. https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2021.pdf

Ministry of Energy and Mineral Resources. (2023). *Decree No. 208.K/EK.05/DJE/2022*. https://drive.esdm.go.id/wl/?id=SE19LZJT8JHbO9ysxpxrv6lmKt58kSQ6

Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., & Verbrugge, A. (2011). *Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/03/Annex-II-Methodology-1.pdf

Motorcycles Data. (2022, July). *McD MotorCycles data*. https://www.motorcyclesdata.com/

Motorcycles Data. (2023, January 30). *Indonesia 2022. Two-wheeler market Up 4.4% accelerating in Q4*. https://www.motorcyclesdata.com/2023/01/30/indonesia-motorcycles/

Murty, D., Kirschbaum, M., Mcmurtrie, R., & Mcgilvray, H. (2002). Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, *8*, 105–123. https://doi.org/10.1046/j.1354-1013.2001.00459.x

National Energy Council. (2019). *Indonesia Energy Outlook 2019*. https://www.den.go.id/index.php/publikasi/index/EnergyOutlook

Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, *2*(12), Article 12. https://doi.org/10.1038/s41560-017-0032-9

Plötz, P., Link, S., Ringelschwendner, H., Keller, M., Moll, C., Bieker, G., Dornoff, J., & Mock, P. (2022). *Real-world usage of plug-in hybrid vehicles in Europe: A 2022 update on fuel consumption, electric driving, and $CO_2$ emissions*. International Council on Clean Transportation. https://theicct.org/publication/real-world-phev-use-jun22/

Plötz, P., Moll, C., Li, Y., Bieker, G., & Mock, P. (2020). *Real-world usage of plug-in hybrid electric vehicles: Fuel consumption, electric driving, and $CO_2$ emissions*. International Council on Clean Transportation. https://theicct.org/publication/real-world-usage-of-plug-in-hybrid-electric-vehicles-fuel-consumption-electric-driving-and-co2-emissions/

Prussi, M., Yugo, M., Prada, L. D., Padella, M., Edwards, R., & Lonza, L. (2020). *JEC well-to-tank report v5*. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/959137

Searle, S. (2019, December 13). *Will someone please tell me if biofuels are good or bad for the environment?* [Blog post]. International Council on Clean Transportation. https://theicct.org/will-someone-please-tell-me-if-biofuels-are-good-or-bad-for-the-environment/

Sopha, B. M., Setiowati, S., & Ma'mun, S. (2016). Environmental assessment of motorcycle using a life-cycle perspective. *Indonesian Journal of Life Cycle Assessment and Sustainability*, *1*(1). https://doi.org/10.52394/ijolcas.v1i1.3

Tankou, A., Bieker, G., & Hall, D. (2023). *Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches*. International Council on Clean Transportation. https://theicct.org/publication/recycling-electric-vehicle-batteries-feb-23/

U.S. Department of Agriculture. (2022). *Indonesia biofuels annual.* https://www.fas.usda.gov/data/indonesia-biofuels-annual-6

U.S. Environmental Protection Agency (U.S. EPA). (2010). *40 CFR Part 80. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program*. https://www.govinfo.gov/content/pkg/FR-2010-03-26/pdf/2010-3851.pdf

U.S. Environmental Protection Agency & U.S. Department of Energy. (2022). *Fuel Economy.* https://www.fueleconomy.gov/

van Gijlswijk, R., Ligterink, N., Bhorasar, A., & Smokers, R. (2022). *Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles—2021.* Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO). https://publications.tno.nl/publication/34639300/erZOUs/TNO-2022-R10409.pdf

World Bank Group and Asian Development Bank. (2021). *Climate Risk Country Profile: Indonesia* https://www.adb.org/sites/default/files/publication/700411/climate-risk-country-profile-indonesia.pdf

Yang, Z., & Yang, L. (2018). *Evaluation of real-world fuel consumption of light-duty vehicles in China*. International Council on Clean Transportation. https://theicct.org/publication/evaluation-of-real-world-fuel-consumption-of-light-duty-vehicles-in-china/

Yuniarto, M. N., Wiratno, S. E., Nugraha, Y. U., Sidharta, I., & Nasruddin, A. (2022). Modeling, Simulation, and Validation of An Electric Scooter Energy Consumption Model: A Case Study of Indonesian Electric Scooter. *IEEE Access*, *10*, 48510–48522. https://doi.org/10.1109/ACCESS.2022.3171860

# APPENDIX

**Table A1.** Global median life-cycle GHG emissions of electricity-generation technologies.

| Type | Electricity-generation technology | Life-cycle GHG emissions (g $CO_{2\ eq.}$/kWh) |
|---|---|---|
| **Non-renewable** | **Coal** | 1001 |
| | **Oil** | 840 |
| | **Natural gas** | 469 |
| | **Nuclear power** | 16 |
| **Renewable** | **Biomass** | 230 [a] |
| | **Geothermal** | 45 |
| | **Solar** | 46 |
| | **Wind** | 12 |
| | **Hydropower** | 4 |

*Source:* IPCC's global median life-cycle GHG emissions of the different electricity-generation technologies (Moomaw et al., 2011);
[a] Adjusted to include land use change emissions (Christensen & Petrenko, 2017)

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION