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Life-cycle greenhouse gas emissions from passenger cars in the European Union

A 2025 update and key factors to consider

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EXECUTIVE SUMMARY

This report is a life-cycle assessment (LCA) of the global warming potential of passenger cars sold in the European Union (EU). It compares sales-weighted average medium segment gasoline, diesel, and natural gas internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel-cell electric vehicles (FCEVs). The analysis covers the greenhouse gas (GHG) emissions from vehicle and battery production and recycling, fuel and electricity production, fuel consumption, and maintenance. This analysis is an update of previous ICCT vehicle LCAs.

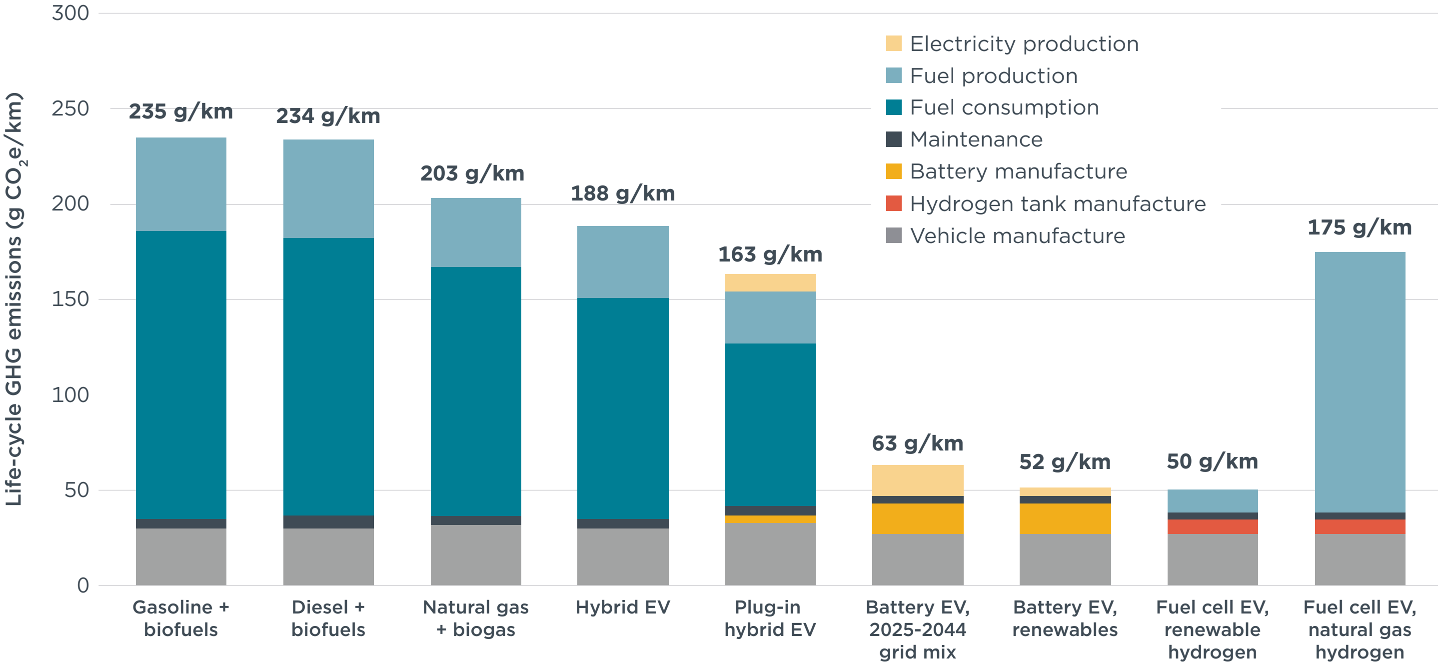
Given the variability in results of life-cycle analyses in the literature and in the context of current efforts by the European Commission and at the United Nations (UNECE) level to harmonize methodologies for reporting vehicle life-cycle emissions, this analysis highlights the impact of key methodological choices on the results. These include assumptions related to fuel and electricity consumption in real-world driving conditions, the full lifetime of passenger cars, and the expected development of the fuel and electricity mix during the lifetime of the vehicles.

Our analysis supports the following conclusions:

The life-cycle emissions of BEVs in the European Union are estimated to be 73% lower than those of gasoline ICEVs. As presented in Figure ES1, BEVs operating on the projected 2025–2044 average EU electricity mix had estimated life-cycle GHG emissions of 63 g CO_2e/km. This is 73% lower than the emissions of gasoline ICEVs running on the average blend of fossil gasoline and ethanol, estimated at 235 g CO_2e/km. These savings go beyond just tailpipe CO_2 emissions: Emissions from fuel production are higher than those from electricity production with the EU average mix. Although BEVs were estimated to have about 40% higher production emissions than ICEVs due to emissions from production of the battery, these additional emissions are more than offset after about 17,000 km of use in the first one or two years. Furthermore, the life-cycle emissions of BEVs were 24% less than estimated in our 2021 LCA (Bieker, 2021), which reflects the ongoing decarbonization of the EU average electricity mix. When using only renewable electricity, BEVs were estimated to produce life-cycle emissions of 52 g CO_2e/km, 78% lower than gasoline ICEVs.

Figure ES1

Life-cycle GHG emissions of medium segment passenger cars sold in the European Union in 2025



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FCEVs are estimated to have low life-cycle emissions only when using renewable electricity-based hydrogen. The emissions of FCEVs running on currently available natural gas-based hydrogen were estimated to be 175 g CO_2e/km, which is 26% lower than the life-cycle emissions of gasoline vehicles. Only when using renewable electricity-based hydrogen, which is still not widely available in the European Union, are the life-cycle emissions of FCEVs similar to those of BEVs, at 50 g CO_2e/km, which is 79% lower than gasoline cars.

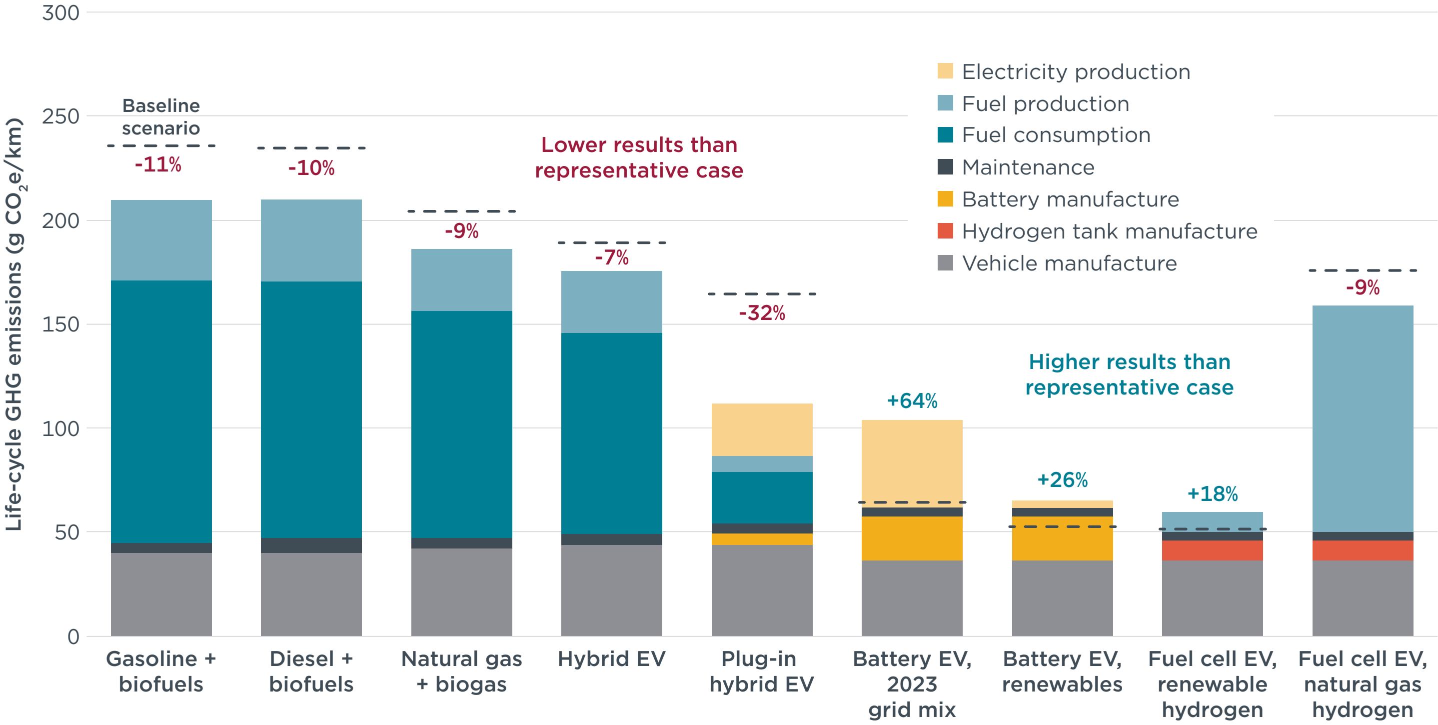
Hybrid and plug-in hybrid vehicles have 20% and 30% lower emissions, respectively, than gasoline ICEVs. The life-cycle GHG emissions of HEVs were estimated at 188 g CO_2e/km, while PHEVs showed emissions of 163 g CO_2e/km when considering average real-world fuel and electricity usage. These values are 20% and 30% lower than gasoline ICEVs, and three times higher than BEVs using the EU average electricity mix.

Diesel cars show similar life-cycle emissions to gasoline cars, and natural gas-powered vehicles are estimated to have emissions only 13% lower. Gasoline and diesel ICEVs showed comparably high life-cycle emissions of 235 g CO_2e/km and 234 g CO_2e/km, respectively. A hypothetical sensitivity scenario for an optimistic uptake of advanced biofuels in the average gasoline and diesel mixes (not shown in the figure) indicated that the life-cycle emissions of ICEVs could be reduced by 0.5%–0.6% for gasoline, hybrid, and plug-in hybrid ICEVs, and 3% for diesel ICEVs. This does not change the observed trends in the climate impact of the powertrain types. Life-cycle emissions of ICEVs powered by compressed natural gas (CNG) were estimated at 203 g CO_2e/km, or 13% lower than ICEVs powered by diesel or gasoline.

Not reflecting the development of the electricity mix over time and using less representative values for vehicle lifetime and fuel and electricity consumption distorts the comparison of powertrain types. Not accounting for the expected changes in the electricity mix inflates the estimated life-cycle emissions of BEVs and slightly increases those of PHEVs. Further, considering only a portion of the average 20-year lifetime of passenger cars in the European Union overestimates the vehicle and battery production emissions allocated per vehicle kilometer across all powertrain types, albeit with a larger impact for BEVs than for other powertrains. Similarly, underestimating the usage phase by not accounting for the discrepancy between real-world and test fuel and electricity consumption benefits gasoline, diesel, and natural gas ICEVs and HEVs more than BEVs and FCEVs. Figure ES2 presents how the combination of these factors distorts the results in comparison to using representative values.

Figure ES2

Life-cycle GHG emissions of medium segment passenger cars sold in the European Union in 2025 using less representative assumptions



Note: Values assume type-approval instead of real-world fuel and electricity consumption values, a static electricity mix instead of accounting for expected improvements in future years, and a 15-year instead of a 20-year vehicle lifetime, and indirect land-use change (ILUC) emissions are excluded.

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When choosing less representative values for each of these factors, the life-cycle emissions of ICEVs and HEVs are underestimated by 7%–11%, while the emissions for PHEVs are underestimated by 32%. These values also include the effect of not accounting for the ILUC emissions of biofuels in the average gasoline, diesel, and CNG mix. For BEVs, in contrast, the life-cycle emissions are overestimated by as much as 64%. As can be observed by comparing Figures ES1 and ES2, PHEVs show almost three times higher emissions than BEVs when choosing representative values for fuel and electricity consumption, vehicle lifetime, and the development of the electricity mix. Considering less representative values for these factors, however, make PHEVs appear to approach the climate benefit of BEVs.

The findings support the following policy considerations:

The phaseout of new ICEV, HEV, and PHEV registrations by 2035 would align sector emissions with EU climate targets. When running on the EU average fuel and electricity mix, only BEVs offer a large-scale reduction in life-cycle GHG emissions. To achieve a similar emissions reduction potential, FCEVs would need to be restricted to the use of renewable electricity-based hydrogen. For ICEVs, HEVs, and PHEVs, meanwhile, the development of the average mix of fossil fuels and biofuels that can be expected from current policies and market developments would not allow vehicles of these powertrain types to meet EU climate targets. While vehicles running solely on e-fuels could, in theory, achieve life-cycle GHG emissions similar to BEVs, the future availability of e-fuels for the road sector is uncertain while costs are expected to remain high.

Decarbonizing all components of the life-cycle emissions of passenger cars could be achieved by complementary policies. Alongside tailpipe CO_2 emission standards and a phaseout of powertrain types that lack large-scale decarbonization potential, complementary policies can decarbonize vehicle production emissions. Examples include the battery production carbon footprint provisions in the EU Battery Regulation and sustainability criteria for vehicle purchase subsidies. Improvements in the energy efficiency of BEVs could be achieved through energy efficiency standards, and decarbonization of the EU power sector can be achieved with the Emissions Trading System.

Emission regulations based on life-cycle emissions could be effective in the long term but come with high uncertainties and administrative burdens and take several years to develop. This analysis shows that comparing the life-cycle GHG emissions of vehicles with different powertrain types is highly sensitive to methodological choices. Basing vehicle regulations on life-cycle emissions thus risks disproportionally benefiting powertrain types that do not offer a sufficient long-term decarbonization potential. Moreover, it would require extensive administrative effort for companies and governments to trace, report, and verify emissions for each step of vehicle production, as well as time to build sufficient capacities and effective cross-industry data sharing platforms. Further, introducing LCA-based regulations would require several years of reporting and negotiation to establish both a baseline and an emissions threshold curve that decreases over time.

Vehicle LCA methodologies should consider the development of the fuel and electricity mix during the lifetime of the vehicles, fuel and electricity consumption values that are representative of average real-world usage, and a full vehicle lifetime. Our analysis of the impact of methodological choices on the estimation of life-cycle emissions illustrates the need to harmonize methodological guidelines. As presented in this study, attaining representative results requires considering projected changes in the fuel and electricity mix during the lifetime of the vehicles, fuel and electricity consumption in real-world driving conditions, and the full lifetime of passenger cars.

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INTRODUCTION

The transportation sector accounts for about 25% of total greenhouse gas (GHG) emissions in the European Union (EU; European Environment Agency [EEA], 2024). Within this sector, 73% of emissions are attributable to road transport. To achieve the European Union's objective of climate neutrality in 2050, emissions from the transport sector need to be reduced by 90% by mid-century compared with 1990 levels (European Commission, 2019). To inform policies to facilitate decarbonization, it is important to understand which powertrain types and fuels could enable the greatest emission reductions over this timeline.

The climate impact of vehicles results from GHG emissions at the tailpipe as well as emissions resulting from the production of fuel and electricity and of vehicles (the latter encompassing material supply chains, vehicle manufacturing, maintenance, recycling, and end-of-life treatment). Vehicle life-cycle assessments (LCA) reflect this comprehensive scope of emissions.

Previous LCA studies have repeatedly demonstrated that battery electric vehicles (BEVs) eliminate tailpipe GHG emissions and represent the most promising pathway for rapidly reducing life-cycle emissions (Bieker, 2021; Hill et al., 2023). Nevertheless, given varying scopes and inconsistent methodological choices, individual LCA studies can yield widely differing and sometimes contradictory results (Andersson & Börjesson, 2021). These inconsistencies may distort comparisons of the climate impact of vehicle types and potentially create uncertainty regarding the optimal set of policies for reducing road transport emissions.

The representativeness of the results of vehicle LCAs heavily depends on the methodology, including assumptions concerning the development of the emissions intensity of the fuel and electricity mixes over time, fuel and electricity consumption in real-world operation, and the full vehicle lifetime. For a comprehensive assessment of the climate impact, land-use change emissions, in particular from biofuel production, and emissions from constructing electricity generation infrastructure can also be considered.

The European Union's 2023 revision of CO_2 emissions standards for passenger cars and light-duty commercial vehicles requires the European Commission to develop a methodology for assessing these vehicles' life-cycle emissions (Regulation (EU) 2019/631). Based on this methodology, manufacturers will be able to voluntarily report the life-cycle emissions of their vehicles from 2026. The development of this methodology runs in parallel to an equivalent effort at the United Nations Economic Commission for Europe (UNECE)'s World Forum for Harmonization of Vehicle Regulations, which hosts an informal working group on developing internationally harmonized guidance for automotive LCAs (UNECE, 2023).

This report presents an updated LCA of the global warming potential of passenger cars sold in the European Union, comparing sales-weighted average medium segment cars of different powertrains and fuel types. It also aims to advance the ongoing discussions regarding the development of representative vehicle LCA methodologies by examining and quantifying the impact of different methodological choices on the results, evaluating these variations, and providing evidence-based recommendations for appropriate methodological assumptions in the EU context.

This report builds upon prior ICCT studies on the life-cycle GHG emissions of passenger cars in Germany (Bieker et al., 2022), Indonesia (Mera & Bieker, 2023), Brazil (Mera et al., 2023), and the United States (O'Malley & Slowik, 2024), and a comparison of vehicle life-cycle emissions in the European Union, China, India, and the United States (Bieker, 2021). By highlighting the importance of methodological choices, this study is intended to help enable a realistic and representative assessment of vehicle life-cycle emissions that can be applied to other global regions.

DATA AND METHODOLOGY

GOAL AND SCOPE

The goal of this study is to compare the 100-year global warming potential of the life-cycle GHG emissions of passenger cars with different powertrain and fuel types within existing policy frameworks in the European Union. We also highlight the impact of methodological choices on LCA outcomes, illustrating possible reasons for the variability in life-cycle analyses results in the literature.

This study considers gasoline-, diesel-, and compressed natural gas (CNG)-powered internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel-cell electric vehicles (FCEVs). For each of these powertrain types, the study illustrates the relative and absolute impact of selected methodological choices.

For a representative comparison of different powertrain types, this study considers sales-weighted average characteristics of medium segment passenger cars registered in the European Union in 2023 (EEA, 2025a).[1] To ensure vehicle characteristics were comparable, sport utility vehicles (SUVs) in the medium segment were not considered in the average. For HEVs, sales-weighted average characteristics could not be determined due to data limitations. Instead, the Toyota Corolla, the top-selling medium segment HEV model in 2023, was used as a representative estimate (EEA, 2025a). For FCEVs, the Toyota Mirai was the only model sold in the medium segment.

This LCA generally follows an attributional approach, meaning it considers the total GHG emissions that can be attributed on average to the vehicle and fuel pathways over their lifetime. Some values, like the indirect land use change (ILUC) emissions of biofuel production, were captured by a consequential approach. The scope of the analysis covers the GHG emissions corresponding to the vehicle cycle. This includes emissions from the production, maintenance, and recycling of vehicles; raw material extraction and processing; component production and assembly; and recycling and disposal at the vehicles' end of life. It also includes the in-service replacement of vehicle parts, such as tires, exhaust and aftertreatment, as well as consumables such as coolant, oil, and urea. For batteries in BEVs and PHEVs, emissions from raw material extraction and processing, cell production, and pack assembly are also considered. Reductions in a vehicle's life-cycle emissions due to the use of batteries in second-life applications and the recovery of battery materials during recycling are not included in this analysis. As the materials recovered from battery recycling reduce the need for raw material mining and processing for future products, battery recycling generally correspond to GHG emissions savings (Tankou et al., 2023).

The study further covers the emissions from the fuel cycle, comprising fuel and electricity production and consumption. For fossil fuels, this includes the entire process from extraction (including flaring) through processing and transportation, fuel refining, and distribution—accounting for all associated methane leakage—and ultimately the final combustion of fuel within vehicles. For biofuels, the scope extends to ILUC emissions resulting from converting land to cultivate biofuel feedstocks, the direct emissions from plant cultivation or waste collection, processing, transportation, and the emissions generated during biofuel production and distribution. For hydrogen, the study differentiates between hydrogen derived from natural gas and that produced from water using renewable electricity. The assessment of natural gas-based hydrogen accounts for GHG emissions from the extraction, processing, and transportation of the

1 The definition of the medium segment is consistent with the European Environment Agency database and Euro car classifications. Models in the medium segment include the Volkswagen Golf.

fossil fuel to emissions released during steam reforming, including methane leakage at all stages. For renewable electricity-based hydrogen, the analysis incorporates life-cycle GHG emissions from electricity generation as well as energy losses during the electrolysis of water process. All hydrogen production pathways in the study consider the energy required for compression and short-distance transport of hydrogen.

The life-cycle emissions of electricity production were evaluated by examining upstream and direct emissions from electricity generation, factoring in infrastructure construction, operations, and decommissioning requirements for energy power plants and considering energy losses that occur during transmission and distribution across the electrical grid, similar to Bieker (2021). The emissions from construction, operation, and decommissioning of electricity generation infrastructure were included as these encompass the life-cycle emissions of renewable electricity production. Energy losses during vehicle charging were included in the vehicles' electricity consumption values. The analysis considers the expected development of the fuel and electricity mixes throughout the lifetime of the vehicles.

The study considers a functional unit of 1 km of distance driven over a vehicle's lifetime. This functional unit effectively is the same as when considering a functional unit of the transportation of one passenger over the distance of 1 km (passenger-kilometer) over the vehicle's lifetime when assuming a vehicle occupancy of one passenger.

VEHICLE CYCLE EMISSIONS

In the vehicle cycle, this study distinguishes between the GHG emissions corresponding to the battery (for BEVs and PHEVs), the hydrogen system (for FCEVs), and the rest of the vehicle.

Vehicle

The GHG emissions corresponding to vehicle production (excluding batteries, hydrogen storage, and the fuel-cell system) were based on a comprehensive LCA study on passenger cars in the European Union and the United Kingdom (Hill et al., 2020). These values, which are relatively similar across powertrains, use a hybrid approach that considers the use of recycled materials in vehicle production and accounts for the benefits of recovering materials during the end-of-life recycling of vehicles (Table 1). Due to their more complex powertrains, ICEVs and PHEVs typically show slightly higher emissions than BEVs and FCEVs. Although not assessed separately by Hill et al. (2020), we considered production emissions of the HEV model to be the same as for conventional gasoline ICEVs. As noted in Bieker (2021), these trends and values are consistent with the findings of other LCA studies.

Table 1
Vehicle production and recycling emissions, excluding battery and hydrogen system

	Vehicle production and recycling emissions (t CO_2e)
Gasoline ICEV	7.2
Diesel ICEV	7.2
CNG ICEV	7.6
HEV	7.2
PHEV	7.9
BEV	6.5
FCEV	6.5

Source: Hill et al. (2020)

Battery

The emissions intensity of battery production was estimated using the 2024 version of Argonne National Laboratory's R&D Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model (Argonne National Laboratory, 2024). The tool includes the emissions from the end-of-life treatment of batteries but does not assign emission credits for the recovery of materials during future recycling. For this study, we adjusted the default R&D GREET values to reflect regional supply chains and battery production, including by accounting for the differences in the electricity mix, based on the input factors described by Kelly et al (2020).

As presented in Table 2, the emissions intensity of lithium-ion batteries varies with the different types of cathode materials and production processes used. In R&D GREET, batteries using lithium iron phosphate (LFP) as a cathode material typically show lower emissions intensity than batteries using lithium nickel manganese cobalt oxide (NMC) cathodes.

Table 2
Battery production emissions intensity in R&D GREET model by region of production and cathode material

kg CO_2e/kWh	Europe	United States	South Korea	Japan	China
LFP	52	57	63	66	69
NMC622	**60**	**64**	**73**	**75**	**80**
NMC811	59	64	72	75	79

As the majority of BEVs and PHEVs currently sold in the European Union use NMC622-based batteries (International Energy Agency [IEA], 2024a), this study considered the emission intensity of this technology. Moreover, based on the IEA's *Global EV Outlook*, the study assumed that 30% of the battery cells used in BEVs and PHEVs sold in the European Union in 2024 were produced domestically, 56% were produced in China, 5% in South Korea, 5% in Japan, and 4% in the United States (IEA, 2025). Weighted by these sales shares, the emissions intensity of NMC622-based batteries used in the European Union was estimated to be 72.8 kg CO_2e/kWh. The sales-weighted average battery capacity of medium segment BEVs and PHEVs sold in the European Union in 2023 were 53.4 kWh and 13.3 kWh, respectively (EEA, 2025a). This results in estimated battery production emissions of 3.9 t CO_2e for BEVs and 1.0 t CO_2e for PHEVs.

Based on the currently available evidence, lithium-ion batteries are expected to last longer than the lifetime of a passenger vehicle. In rigid battery durability tests, NMC batteries have been demonstrated to sustain more than 80% of their initial capacity even after 3,000–5,000 equivalent full cycles (Harlow et al., 2019; Schmalstieg et al., 2014). LFP batteries have been shown to remain above that value even after 5,000–6,000 equivalent full cycles (Naumann et al., 2020; Spingler et al., 2020). This high battery durability is largely confirmed in data from real-world BEV usage, even when accounting for usage-dependent variations (Hackmann et al., 2024). For BEVs with a range of 200–400 km, a battery lifetime of 3,000–5,000 equivalent full cycles would correspond to a mileage of 600,000–2,000,000 km. This is several times higher than the average lifetime mileage of passenger cars of 240,000 km. Based on data from 20,000 vehicles, Recurrent found that for BEVs sold after 2016, outside of recalls, less than 1% have reported battery replacements (Najman, 2024).

For PHEVs, whose battery needs to be fully charged and discharged frequently, a considerable degradation of capacity is observed in the first years of operation. As shown by Pavlovic et al. (2024), this may decrease the realized electric driving share and thus increase real-world fuel consumption. Given the limited availability of data on this effect, this study optimistically assumes that the real-world fuel consumption observed for new vehicles will remain constant during the vehicle lifetime.

Hydrogen system

The hydrogen system in FCEVs consists of a hydrogen tank and fuel cell, and its emissions are mostly due to the use of carbon fiber reinforced plastics needed for the hydrogen tank. This study considered emissions of 1.8 t CO_2e for the hydrogen system, based on the 2024 version of R&D GREET (Wang et al., 2025).

Lifetime and lifetime mileage

A full vehicle lifetime spans from vehicle production through end-of-life management and recycling. A representative average vehicle lifetime can thus be estimated based on the average age of end-of-life vehicles. Table 3 presents the average age of end-of-life vehicles collected in seven EU Member States from 2022 to 2024. They range between about 19 years in Germany and Belgium and 24 years in Portugal.

Table 3
Average age of end-of-life vehicles reported in a selection of EU Member States

Country	Year	Average age of end-of-life vehicles (years)	Source
Belgium	2022	18.5	Febelauto (2023)
Finland	2024	22.8	Autoalan Tiedotuskeskus (2025)
France	2022	19.8	Agence de la Transition Écologique (2024)
Germany	2022	18.6	Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (2024)
Netherlands	2023	19.6	Auto Recycling Nederland (2024)
Portugal	2022	23.8	Agência Portuguesa do Ambiente (2024)
Spain	2023	21.1	Sigrauto (2024)

Based on these findings, this study considered an average vehicle lifetime of 20 years. This number is considered a conservative estimate, as it lies at the lower end of the range of values found for the EU Member States. For comparison, the SIBYL model considers an average EU passenger car lifetime of 25 years (e:misia, n.d.). Further, the lifetime of vehicles recycled today corresponds to vehicles produced around the year 2000, and the durability of vehicles has improved since that time. Reports for Germany, Belgium, Finland, France, Portugal, Spain indicate a continuous increase in the average age of collected end-of-life vehicles, which is also mirrored in the data sources evaluated for previous ICCT reports (Bieker, 2021). This increase in vehicle lifetime is also reflected in the growing average age of vehicles circulating in the European Union (ACEA, 2024), which can be explained in part by higher durability and higher vehicles prices (Zacharof et al., 2025).

The average age of vehicles leaving the road, which can be based on trade and de-registration data (Held et al., 2021) or conformity test data (Nguyen-Tien et al., 2025), is different from the average total vehicle lifetime. These estimates include a share of vehicles being exported before reaching their end of life, sometimes after being driven for only a few years. For countries that export a significant number of cars as used vehicles, as is the case for many EU countries, this can result in a significant difference between the average age of vehicles when they are de-registered and the average full vehicle lifetime.

The average annual mileage of passenger cars in Germany is conservatively 12,000 km (Kraftfahrt-Bundesamt, 2024), and similar values have been reported for the annual distance traveled by car in EU Member States (Agence de la Transition Écologique et al., 2025; European Automobile Manufacturers' Association, 2025). Assuming a 20-year lifetime, this study considered an average lifetime mileage of 240,000 km. This estimate is similar to the average lifetime mileages of EU passenger cars considered in the SIBYL model (e:misia, n.d.) and reported by other Member States (Ministères Aménagement du Territoire Transition Écologique, 2024).

Vehicles' annual mileage typically decreases as they age. With more kilometers per year driven in the initial years, the relatively higher emissions intensity of the electricity mixes during this period must be accounted for with a higher weighting than the relatively lower projected emissions intensity in later years. Based on the development of annual mileage over vehicle age in Germany (Bäumer et al., 2017), this study considered a 5% decrease in annual mileage per year. This implies that at a vehicle age of 15 years, for example, the annual mileage is only half the mileage of a new vehicle. Alternatively, the development of annual mileage can also be approached with a linear decrease.

Maintenance

The GHG emissions of maintenance cover repairs and in-service replacement of consumables, including tires, exhaust and aftertreatment, coolant, oil, urea, and others. The list of materials slightly varies between powertrain types. While diesel cars consume urea in the exhaust aftertreatment and have higher maintenance emissions, the electric motors of BEVs and FCEVs use less consumables than their combustion engine equivalents. This study considered maintenance GHG emissions of 5 g CO_2e/km for gasoline- and CNG-powered ICEVs, HEVs, and PHEVs; 7 g CO_2e/km for diesel ICEVs; and 4 g CO_2e/km for BEVs and FCEVs (Hill et al., 2020).

FUEL CYCLE EMISSIONS

Fuel and energy consumption

As demonstrated by a large body of ICCT studies in the European Union (Dornoff et al., 2024), China (Wu et al., 2021), and the United States and Japan (Tietge et al., 2017), the average fuel consumption of ICEVs and HEVs reported by hundreds of thousands of consumers is observed to significantly exceed the official test values. This mainly results from official test cycles not fully covering a representative use case of vehicles. Importantly, these studies indicate a growing gap between real-world and type-approval fuel consumption figures across test cycles and markets globally.

In response to a growing gap between real-world and Worldwide harmonized Light vehicles Test Procedure (WLTP) values, the European Commission monitors the fuel consumption data of vehicles sold from 2021 through on-board fuel consumption meters (OBFCMs). Based on data from 2.9 million vehicles sold in 2021 and 2022, the EEA (2025b) found that the WLTP underestimated the real-world fuel consumption of gasoline ICEVs and HEVs by an average of about +20%, while a gap of +18% was observed for diesel ICEVs. For ICEVs powered by CNG, this study assumed a similar deviation of +20%.

Table 4 displays the sales-weighted average of official WLTP fuel and electricity consumption of medium segment ICEVs, PHEVs, BEVs, and FCEVs sold in the European Union in 2023 (EEA, 2025a), as well as the highest selling medium segment HEV model, the Toyota Corolla. Based on the average deviation of real-world and

WLTP fuel consumption reported by the EEA, the WLTP fuel consumption values for ICEVs and HEVs were adjusted to reflect a more representative usage. The real-world electricity consumption of BEVs was estimated by a recent TNO study to be around +25% higher than the WLTP test value (Schouten, 2024). Given a lack of large-scale evidence for the real-world usage of FCEVs, this study considered the hydrogen consumption of the Toyota Mirai in 2023 (Allgemeiner Deutscher Automobil-Club, 2023), which is +25% above the WLTP value.

Table 4
WLTP and real-world fuel and electricity consumption values for the selected vehicles

Powertrain type	WLTP fuel and energy consumption	Real-world fuel and energy consumption
Gasoline blend ICEV	5.7 L/100 km	6.9 L/100 km
Diesel blend ICEV	4.9 L/100 km	5.8 L/100 km
Natural gas blend ICEV	3.9 kg/100 km	4.7 kg/100 km
HEV (gasoline)	4.4 L/100 km	5.3 L/100 km
PHEV (gasoline)	1.1 L/100 km + 15.2 kWh/100 km	3.8 L/100 km + 11.9 kWh/100 km
BEV	16.2 kWh/100 km	20.2 kWh/100 km
FCEV	0.8 kg/100 km	1.0 kg/100 km

For PHEVs, fuel and electricity consumption is largely determined by the extent to which they are driven with a charged battery—in other words, in the predominantly but typically not fully electric charge-depleting (CD) mode—and how much they are driven in charge-sustaining mode using the combustion engine (Bieker et al., 2022). In the WLTP and other test cycles, the CD mode drive share is estimated as a function of the tested range of a vehicle in CD mode, referred to as the utility factor.

In the initial version of the WLTP and in the New European Driving Cycle (NEDC), the utility factor assumed that a PHEV starts every day with a fully charged battery and is driven in CD mode as much as possible. As found in studies by the ICCT and Fraunhofer ISI (Plötz et al., 2020; 2022), this assumption reflects an idealized usage profile. For instance, based on evidence from tens of thousands of PHEV users in the European Union, Plötz et al. (2022) found that the fuel consumption of privately owned PHEVs exceeded WLTP values by a factor of 3 on average, while a deviation factor of 5 was determined for company car drivers. These findings were substantiated by data collected from OBFCMs showing a +240% higher fuel consumption than WLTP values for PHEVs sold in 2021 and a +306% higher consumption for vehicles sold in 2022 (EEA, 2025b). Similar results were found for PHEVs driven in the United States (Isenstadt et al., 2022).

In response to the observed differences between test and real-world fuel consumption, the European Commission updated the CD mode drive share assumption for PHEV models type approved from 2025 onwards and will further refine these assumptions for models type approved from 2027 (Commission Regulation (EU) 2023/443, 2023). With these updates, the deviation of the fuel and electricity consumption of PHEVs sold in the European Union are expected to approach the real-world deviation values currently observed for ICEVs, HEVs, and BEVs.

For this study, average WLTP fuel and electricity consumption values were sourced from sales-weighted averages of vehicles sold in 2023. The fuel consumption figures were adjusted to representative real-world driving conditions with the average +240%

deviation reported by the EEA (2025b). This correction implies that PHEVs are driven less in CD mode, and thus less on electricity: PHEV models with a WLTP-equivalent all-electric range of 60 km realize an electric driving share of 50%, while the WLTP values imply 80% (Plötz et al., 2022). Assuming that the sales-weighted average WLTP electricity consumption of 15.2 kWh/100 km is based on an 80% electric driving share, the value translates into 9.5 kWh/100 km for a 50% electric driving share. Adding the +25% discrepancy factor for BEVs results in an average real-world electricity consumption of 11.9 kWh/100 km.

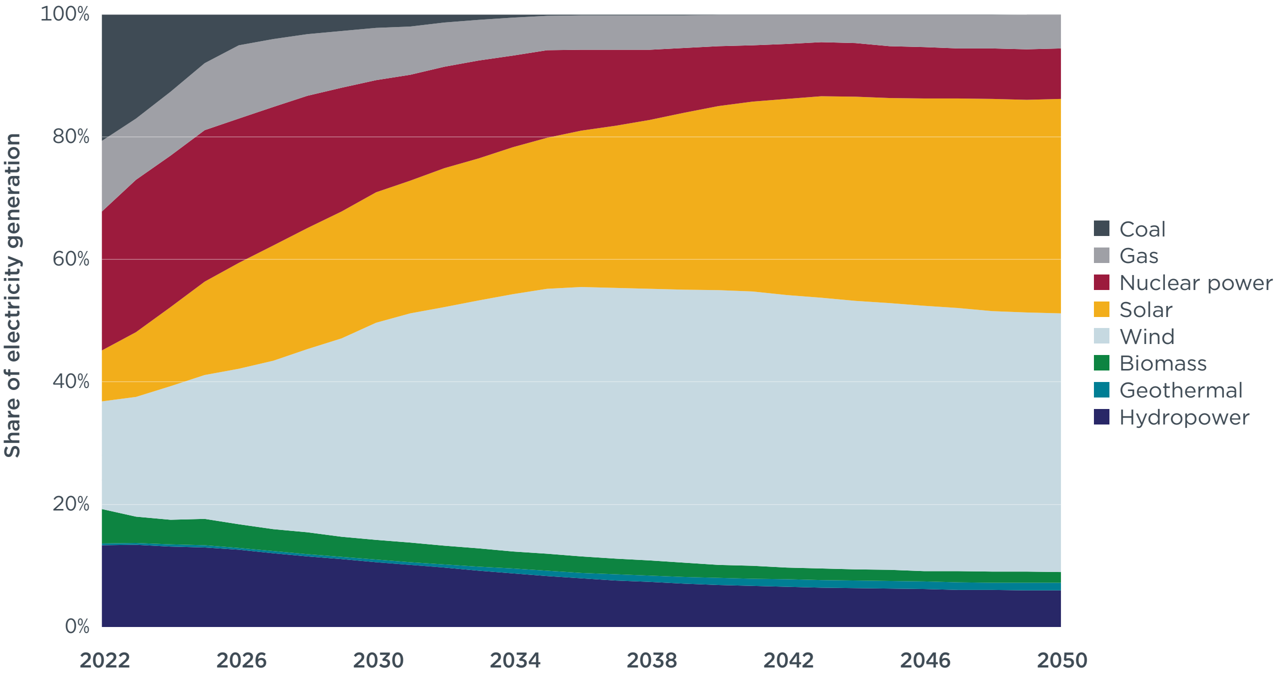
Given expected decay in battery capacity, and thus in the CD mode range of PHEV models, it is expected that the electric driving share of PHEVs will decrease during the vehicle's lifetime. This effect is expected to increase the average real-world fuel consumption of PHEVs further than observed in OBFCM data for new vehicles. Due to data limitations, however, this effect was not accounted for in the analysis.

Emissions intensity of electricity

The share of renewable electricity in the European Union's power sector has increased over the past decade, leading to an ongoing decline in emissions intensity (IEA, n.d.). This can be attributed to policy frameworks such as the EU Emissions Trading System, the continuously falling costs of solar and wind power, and cost increases for coal- and natural-gas based power plants (Kost et al. 2024). Although it is uncertain whether these trends will persist in the future, there is a consensus that the emissions intensity of electricity generation will likely continue to decrease overall (IEA, 2024b). With a vehicle lifetime of at least 20 years, vehicles sold in 2025 will be used until 2044 and experience an ever-changing electricity mix over that period.

Figure 1 presents the future shares of technologies in electricity generation as projected by the European Commission Joint Research Centre (JRC)'s POTEnCIA CETO 2024 scenario (JRC, 2024), which is used as the baseline scenario in this study. This scenario models the contribution of each power generation technology to EU climate objectives based on the current EU policy framework and expected cost developments of power-generation technologies.

Figure 1
Projected share of electricity generation by technology



Notes: Coal includes both hard coal and lignite. Gas includes natural gas, derived gas, and refinery gas. Solar includes both photovoltaic and thermal solar. Wind includes both on-shore and off-shore generation. Oil and tide, wave, and ocean energy generation technologies are excluded from the figure, as they make up less than 1% of the share of electricity generation.

Source: Joint Research Centre (2024)

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To translate the shares of electricity generation to the emissions intensity of electricity supply, we weighted the shares with EU-specific life-cycle emission intensities from a recent UNECE (2022) report, as presented in Table 5. These values are very similar to the global median life-cycle emission intensity values of electricity generation technologies provided by the Intergovernmental Panel on Climate Change (IPCC; Moomaw et al., 2011). In cases where electricity generation technologies were not covered in the UNECE report, such as for geothermal energy or oil, we used emissions intensities for geothermal power from the IPCC. EU-specific values for stationary biomass combustion are from ICCT analyses (Christensen & Petrenko, 2017).

Besides emissions occurring directly from the combustion of fuels at power plants, UNECE's life-cycle emission factors include upstream emissions from fuel production, processing, and transport, as well as the construction and grid connection emissions of electricity generation infrastructure. As shown in Table 5, emissions related to electricity generation infrastructure can make up a significant share of life-cycle emissions, including up to 100% for renewable energy sources.

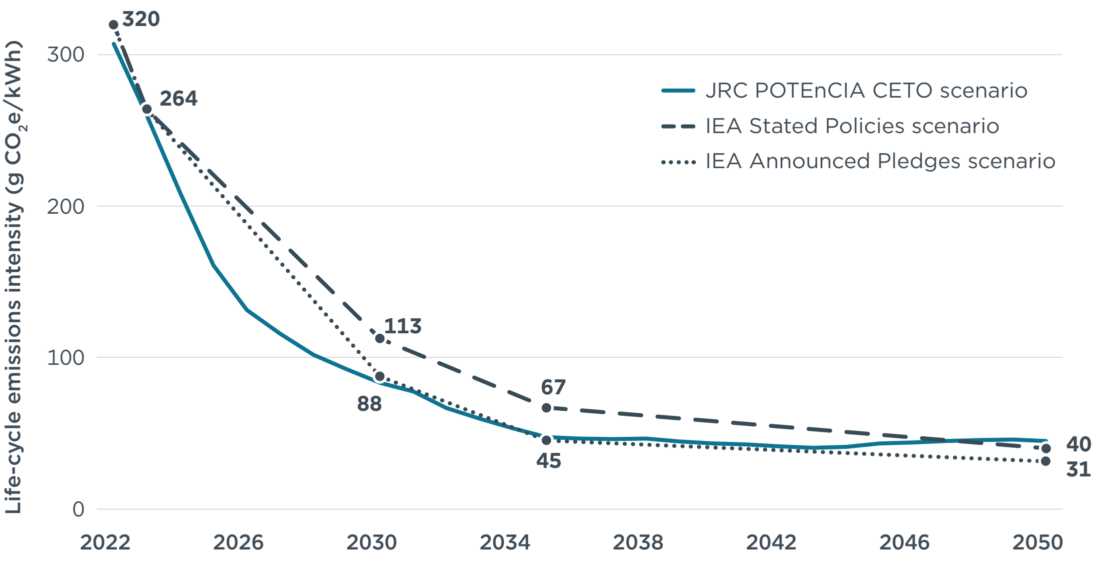
Table 5
Life-cycle GHG emissions intensity of electricity generation technologies

	Electricity generation technology	Life-cycle GHG emission intensity (g CO_2e/kWh)	Share of power plant construction and grid connection
Non-renewable	Coal	1023	<1%
	Natural gas	434	<1%
	Nuclear	5.1	~15%
Renewable	Photovoltaic (PV)	36.7	~98%
	Wind, offshore	14.2	100%
	Wind, onshore	12.4	~98%
	Hydropower	10.7	100%

Source: UNECE (2022)

Figure 2 reports the life-cycle GHG emissions of the electricity mix using the JRC scenario and two IEA scenarios: the Stated Policies Scenario, which similarly evaluates the effect of policies already in place or announced, and the Announced Pledges Scenario, which assumes that governments' climate commitments are met in full and on time (IEA, 2024b). The figure accounts for 6% transmission and distribution losses in the grid (World Bank Group, n.d.).

Figure 2
Life-cycle GHG emissions intensity of the electricity mix from three scenarios



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For a BEV or PHEV purchased in 2025 and driven for 20 years (accounting for a 5% decrease in mileage annually), the future shares of electricity generation technologies in the JRC's POTEnCIA CETO 2024 scenario result in a lifetime average life-cycle emissions intensity of 78 g CO_2e/kWh for electricity production and distribution. Based on the future technology shares in the IEA's Stated Policies Scenario, the emissions intensity would be 112 g of CO_2e/kWh. As indicated in Figure 2, the emissions intensity of the IEA's electricity mix projection linearly interpolates between data points provided in 5-year increments. When compared with the JRC scenario, this linear interpolation appears to contribute to the apparently higher values in the IEA scenarios.

The latest non-projected electricity mix data in the JRC and IEA reports are from 2023. The JRC's 2023 electricity production mix translates into a life-cycle emissions intensity of 260 g CO_2e/kWh. This is 2 to 3 times higher than the expected average emission intensity over the vehicle's 2025–2044 lifetime.

Table 6
Life-cycle GHG emissions intensity of electricity during the BEV and PHEV usage phase under three scenarios

Scenario	Emissions intensity of electricity	Reference year(s)
Historic electricity mix	260 g CO_2e/kWh	2023
JRC's POTEnCIA CETO scenario	78 g CO_2e/kWh	2025–2044
IEA's Stated Policies Scenario	112 g CO_2e/kWh	2025–2044

When considering only the use of renewable electricity, we considered a future 2:1 share of wind and solar power generation in the European Union (JRC, 2024), which yielded a life-cycle emission intensity of 21 g CO_2e/kWh.

Emissions intensity of average fuel blends

Like the average electricity mix, the development of average gasoline, diesel, and CNG blends over the lifetime of cars also need to be considered. Unlike the power sector, where market dynamics have made the cost of renewables fall below their fossil alternatives, fossil gasoline, diesel, and natural gas are expected to remain cheaper to produce than biofuels or renewable electricity-based alternatives (O'Malley & Pavlenko, 2022). In some cases, this is because of characteristics inherent to production pathways and the higher costs of vegetable oil feedstocks (O'Malley et al., 2022). Policies such as expanding the EU Emissions Trading System to include road transport may help narrow the cost differential (European Commission, n.d), but it is uncertain whether the price of allowances for burning fossil fuels will be sufficiently high to bridge this cost gap. We thus do not expect biofuels to become cheaper than fossil fuels over the timeframe studied in our analysis. Any changes in future average fuel blends are expected to continue to be determined by policies.

In the European Union, the most important policies influencing fuel blends are the renewable energy share targets for transport in the Renewable Energy Directive. The most recent revision (RED III; Directive (EU) 2023/2413) set updated sustainability criteria for biofuels, while provisions on high-ILUC risk categories were introduced in a delegated act after RED II (Baldino, 2023). ILUC refers to the changes in global land use made in response to policies and market demand for a given fuel. For example, when agricultural land is cultivated to produce biofuel feedstocks like corn or soybeans, this may divert crops grown for other uses such as food and animal feed production; to compensate, agricultural land is expanded by converting natural ecosystems elsewhere, which can release significant amounts of stored carbon from the soil and above- and below-ground biomass (Pavlenko & Searle, 2018). Certain biofuels designated as high-ILUC risk (those produced from feedstocks that drive significant expansion into high-carbon stock land), must be phased out by EU Member States from their RED targets by 2030. At present, only biofuel produced from palm oil is considered high-ILUC risk. Some Member States have already phased out palm oil from their national implementation of the RED.

Other conventional biofuels, such as those based on corn and soybean, are also prone to ILUC. To limit the expansion of land use for these feedstocks, RED III caps the eligible shares of biofuels produced from food and feed crops (Baldino, 2023). Moreover, the directive supports the sourcing of advanced biofuels, based on residues and wastes, within a 5.5% advanced biofuel and renewable fuels of non-biological origin (RFNBO) sub-quota. This is discussed in the e-fuels section below.

Additionally, some advanced biofuel feedstocks like used cooking oil have inherently limited availability and fraud risk (O'Malley & Baldino, 2024). To mitigate this risk, the RED II established a cap on the share of biofuels produced from Annex IX, Part B feedstocks, including used cooking oil, and category 1 and 2 animal fats. However, challenges persist in detecting fraud, particularly regarding imported biofuels (O'Malley & Baldino, 2024).

The average gasoline blend in the European Union contains 4.7% ethanol by energy (IEA Bioenergy, 2024), which corresponds to an average volumetric ethanol share of 7%. Ethanol is typically blended at the pump in E5 (up to 5vol.%) and E10 (10vol.%) quantities. The average volumetric ethanol share of 7% thus corresponds to an approximately equal consumption of E5 and E10. Diesel blends contain shares of biodiesel and hydrogenated vegetable oil (HVO) with an overall share of 7vol.% (B7; IEA Bioenergy, 2024). For the share of biomethane in the natural gas blend, we have considered an optimistic 2030 scenario of 3.4vol.% of biomethane (Prussi et al., 2020). This blend is considered for the full 2025–2044 vehicle life.

Table 7 lists the current mix of feedstocks for the European Union's ethanol and biodiesel/HVO consumption mix (Flach et al., 2024). The biomethane mix considered includes corn (40%), organic waste (40%), and manure-based biomethane (20%; Prussi et al., 2020). The biofuel blends reflect RED III provisions and are considered for the entire lifetime of vehicles in this study. We assumed that no further policy is adopted that would substantially alter future blend shares.

Table 7
Feedstocks used for biofuels production in the European Union

Share of feedstocks in ethanol mix in 2024		Share of feedstock in combined biodiesel and HVO mix in 2024	
Corn kernels	59%	**Rapeseed oil**	43%
Wheat kernels	22%	**Used cooking oil**	23%
Triticale	7%	**Animal fats**	6%
Barley kernels	3%	**Soybean oil**	6%
Rye kernels	2%	**Sunflower oil**	2%
Sugar beets	7%	**Palm oil**	1%
Cellulosic biomass	1%	**Other residual oils**	18%

Notes: Other residual oils include pine oil, tall oil, tall oil pitch, palm fatty acid distillates (PFAD), palm oil mill effluents, empty palm fruit bunches, free fatty acids, and sewage sludge.
Source: Flach et al. (2024)

For this study, we included a sensitivity on possible future blends of advanced biofuels in the mix. The RED III targets include a share of approximatively 2.75% by energy (5.5% including multipliers) of advanced biofuels, renewable electricity-based hydrogen, and other RFNBOs for the whole transportation sector by 2030, including hydrogen used in oil refining. Out of this target, at least 1 percentage point is set to come from RFNBOs in 2030. As RFNBOs, e-fuels would be eligible to contribute to these targets, but it remains uncertain how the 2.75% quota will be split between advanced biofuels, hydrogen, and e-fuels. Furthermore, it is uncertain if any available e-fuel supply would be directed toward the average fuel blends in road transport or used for cars running solely on e-fuels, or if they would be directed towards aviation and shipping. It is unlikely that e-fuels will be consumed in road transport due to their high costs and currently limited availability, and given the multipliers of 1.2 for advanced biofuels and 1.5 for RFNBOs in the RED III when these fuels are consumed in aviation and shipping.

The share of used cooking oil, other residual oils, and tallow HVO could also increase due to rising aviation fuel blending mandates. HVO is a distillate fuel and co-product of hydroprocessed esters and fatty acids (HEFA) refining, which is expected to remain the primary sustainable aviation fuel production pathway in the European Union until well into the next decade. However, the consumption of used cooking oil and tallow in transport fuels will be limited due to the RED III 1.7% cap on Annex IX, Part B feedstocks. This cap will remain in place through at least 2030.

All that considered, we expect substantial uncertainty in a potential future increase in the usage of advanced and other biofuels in the road sector; therefore, we explore the sensitivity of our results to higher biofuel blends in a sensitivity analysis. In a hypothetical scenario, we assumed the volume share of biofuels in the average diesel blend linearly increases from the current 7% until doubling to 14% in 2040. As a hypothetical sensitivity and not necessarily a realistic scenario, we further assumed that all of the additional biodiesel and HVO shares could be met solely with other residual oils such as palm oil mill effluent and tall oil not included in the RED III 1.7% cap. For the share of ethanol in the gasoline blend, we assumed that the blend rate would increase to the technical blending limit of current gasoline vehicles in the European Union, of 10% by volume. We also assumed that the share of food-based ethanol consumed in gasoline remains constant while all the additional shares come from advanced biofuels (e.g., cellulosic feedstocks). Our sensitivity analysis is designed as an illustrative scenario and does not aim to evaluate future changes in European Union policy. Results for this scenario are reported with error bars in the gasoline and diesel results.

For the emission intensities of the individual fossil fuel and biofuel pathways, this study distinguishes between the emissions corresponding to fuel production and transport (well-to-tank, WTT), which includes ILUC emissions in the case of many biofuel pathways, and emissions during fuel consumption (tank-to-wheel, TTW). For the biofuel pathways, the CO_2 emissions during fuel combustion are not accounted for, to offset the CO_2 uptake during plant growth.

Table 8 summarizes the emission intensities of the average gasoline, diesel, and natural gas blends, as well as the emissions intensity for the average of their fossil and biofuel components. For fossil gasoline, diesel and natural gas, the emissions intensities are provided by the EU Fuel Quality Directive (Council Directive (EU) 2015/652, 2015) and a report by the JEC, a consortium of the Joint Research Centre, European Council for Automotive R&D, and Concawe (Prussi et al., 2020). In the case of natural gas, these are updated with higher methane leakage emissions occurring during natural gas production and transport (7.8 g CO_2e/MJ, based on R&D GREET), as described by Bieker (2021).[2] With a recent shift towards more natural gas supply to the European Union via liquefied natural gas ships, emissions from upstream leakage are expected to increase.

2 Upstream methane emissions amount to 0.26 g methane (CH_4) per MJ of natural gas and 0.05 g CH_4 per MJ of gasoline, and these are expected to be similar in other regions. For natural gas, these emissions correspond to a 100-year global warming potential of 7.8 g CO_2e/MJ.

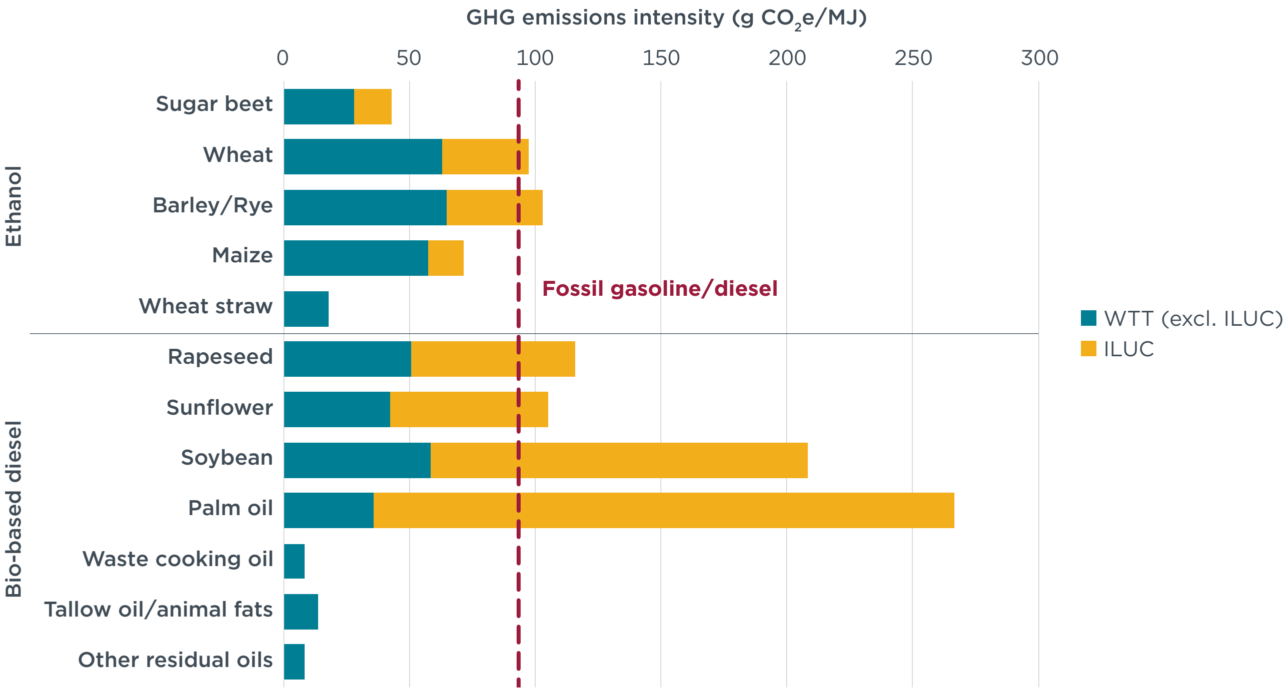
Table 8
GHG emissions intensity of fuels mix assumed for the study

Fuel	Well-to-wheel emissions (including ILUC) (g CO_2e/MJ)	Well-to-tank emissions (excluding ILUC) (g CO_2e/MJ)	ILUC emissions (g CO_2e/MJ)	Tank-to-wheel emissions (g CO_2e/MJ)
Gasoline, including biofuels (7vol.%)	**92.6**	21.6	1.0	70.0
Fossil gasoline	**93.3**	19.9	–	73.4
Ethanol	**78.4**	57.3	21.1	0
Diesel, including biofuels (7vol.%)	**93.4**	22.5	2.8	68.1
Fossil diesel	**95.1**	21.9	–	73.2
Bio-based diesel (biodiesel and HVO)	**71.0**	30.9	40.1	0
Natural gas, including biogas (3vol.%)	**74.1**	15.9	0.3	57.9
Natural gas	**76.6**	16.7	–	59.9
Biogas	**2.1**	-6.3	8.4	0

The life-cycle emission intensities of the individual biofuel pathways are provided in Figure 3. Emission intensities are again based on JEC reports (Huss & Weingerl, 2020; Prussi et al., 2020) and complemented with ILUC emissions estimates from the GLOBIOM model (Valin et al., 2015). For the "other oils" category reported by the U.S. Department of Agriculture (USDA; Flach et al., 2024), we used the emissions intensity of the used cooking oil pathway in the JEC report for biodiesel and HVO. This is likely an underestimate; for example, USDA's classification includes palm fatty acid distillates, which are associated with high GHG emissions (Malins, 2017).

As shown in Figure 3, depending on the feedstock, ILUC emissions can correspond to a significant share of the overall life-cycle emissions.

Figure 3
GHG emissions intensity of biofuels pathways



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The TTW emissions for the fossil fuel pathways presented here assume a full oxidation of the fuels to CO_2. In reality, however, this reaction is not always complete, leaving some methane (CH_4), other hydrocarbons, and particulate matter in the exhaust emissions. In addition, the combustion of gasoline and diesel produces nitrous oxide (N_2O) emissions. As described in Bieker (2021), methane and nitrous oxide emissions accumulate additional TTW GHG emissions of about 1 g CO_2e/km for gasoline, 4 g CO_2e/km for diesel, and 2 g CO_2e/km for CNG cars. For HEVs and PHEVs, the same emissions as for gasoline cars were considered. Notably, these non-CO_2 emissions from the combustion engine also apply to renewable diesel such as e-fuel powered vehicles.

E-fuels

The life-cycle GHG emissions of e-fuels are determined by the energy consumption of hydrogen production, CO_2 sourced from industrial exhaust gases or through direct air capture, and fuel synthesis. In total, these three production steps correspond to an energy demand of about 2 MJ electricity/MJ e-fuel, relatively independent of the fuel production process (Heinemann et al., 2019; Prussi et al., 2020). In other words, the e-fuel production process alone corresponds to energy losses of about 50%. Multiplied by the life-cycle emissions intensity of electricity generation from wind and solar power as provided above, the life-cycle GHG emissions of e-fuels are estimated at 11.5 g CO_2e/MJ.

As discussed above, e-fuels are generally not expected to be blended in the average fuel mix for vehicles purchased in 2025. This is due to their high costs, limited amounts in the foreseeable future, and the absence of a policy requiring their usage in road transport. Accordingly, the JRC's POTEnCIA CETO 2024 scenario (JRC, 2024) also does not consider the application of synthetic liquid fuels in road transport. We have, however, added a scenario for using e-fuels in passenger cars. Rather than assuming that e-fuels are blended in the average gasoline and diesel blends, the scenario considers their use in vehicles that solely run on e-fuels. This scenario is presented in the results section (Figure 9).

Hydrogen

This report compares the life-cycle GHG emissions of FCEVs using hydrogen produced from steam reforming of natural gas (grey hydrogen) with those using electrolysis-based hydrogen produced from only renewable electricity (green hydrogen). Hydrogen produced from (unabated) natural gas corresponded to 90% of global production in 2023, with by-product hydrogen (9%) making up most of the rest; the share of electricity-based hydrogen was below 0.4% (European Hydrogen Observatory, 2024). Still, renewable electricity-based hydrogen is anticipated to become the dominant pathway in the future (European Hydrogen Observatory, 2024).

The life-cycle GHG emissions of natural gas-based hydrogen are estimated to be 113 g CO_2e/MJ (13.6 kg CO_2e/kg), based on the JEC report (Prussi et al., 2020) and updated with higher methane leakage emissions from natural gas production and transport as described by Bieker (2021). For electricity-based hydrogen, the life-cycle GHG emissions are estimated to be 9.8 g CO_2e/MJ (1.2 kg CO_2e/kg), based on the emissions intensity of renewable electricity production and an energy demand of 1.69 MJ electricity per MJ of hydrogen from production and compression. This energy demand considers the production of hydrogen by electrolysis with an energy efficiency of 70% (Prussi et al., 2020), which corresponds to an energy loss of 0.43 MJ per MJ of hydrogen. It further includes energy losses of 0.25 MJ per MJ of hydrogen that occurs during hydrogen compression (Prussi et al., 2020). Both pathways include the energy losses and emissions corresponding to the compression and short-distance transport of hydrogen. The energy losses of long-distance transport are not addressed in this study.

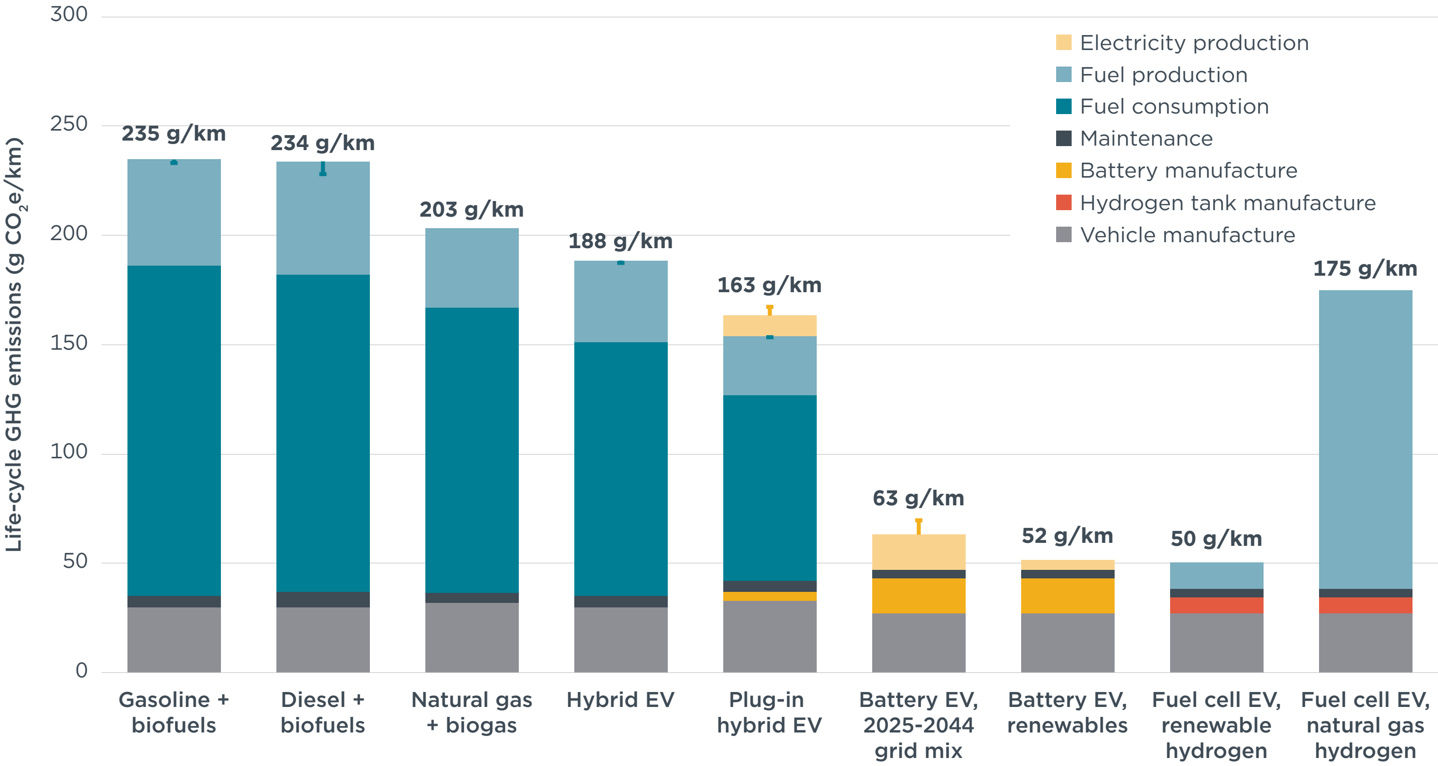
RESULTS

Figure 4 presents the life-cycle GHG emissions of the selected powertrain types in our baseline case, which considers the most representative methodological choices regarding the expected development of the fuel and electricity mix, real-world fuel and electricity consumption, and vehicle lifetime. For a comprehensive assessment of climate impact, the baseline case further considers emissions from ILUC and the impact of electricity generation infrastructure emissions.

Both the "gasoline + biofuels" and the "diesel + biofuels" blends consider a 7vol.% share of biofuels, while the "natural gas + biogas" blend considers a 3.4vol.% share of biomethane, as explained above.

Figure 4

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025, by powertrain type



Notes: The yellow error bars indicate the difference between the development of the electricity mix according to the JRC's (2024) POTEnCIA CETO scenario (our baseline case) and the IEA's (2024b) Stated Policy Scenario. The blue error bars compare the RED III compatible fuel mix scenario (our baseline case) with a hypothetical scenario of largely increased advanced biofuels shares.

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As presented in Figure 4, ICEVs powered by the average gasoline and average diesel mix showed similar life-cycle GHG emissions, of 235 g CO_2e/km and 234 g CO_2e/km, respectively. Natural gas-powered ICEVs produced an estimated 203 g CO_2e/km, 13% lower than gasoline ICEVs. HEVs and PHEVs had similar life-cycle GHG emissions, of 188 g CO_2e/km and 163 g CO_2e/km, respectively, 20%–30% lower than the conventional gasoline ICEV comparator. These results indicate that hybridization does offer a life-cycle GHG emission benefit compared with conventional ICEVs, but it is relatively small compared with other powertrains.

The blue error bars indicate sensitivity scenarios for a hypothetical case of a large increase in advanced biofuel shares in the gasoline and diesel blends. In this illustrative scenario, the share of biofuels in the diesel blend doubles by 2040, and the share of ethanol in the gasoline blend approaches the 10vol.% blending limit for current EU gasoline vehicles. In both cases, the additional biofuel shares are assumed to be fully met with advanced biofuels, such as cellulosic ethanol and residues-based biodiesel and HVO. Even with this optimistic scenario, the life-cycle emissions of gasoline ICEVs, HEVs, and PHEVs are only 0.5%–0.6% lower than in the baseline case. For diesel ICEVs, the higher increase in biodiesel and HVO results in 3% lower life-cycle emissions. This result indicates that even with optimistic scenarios for the development of the average gasoline and diesel blend, the impact on the vehicles' life-cycle emissions is only marginal.

In contrast, BEVs running on the average electricity mix—considering the 20-year vehicle lifetime mix change—showed life-cycle GHG emissions of 63 g CO_2e/km, 73% lower than conventional gasoline ICEVs. These savings go beyond just tailpipe CO_2 emissions, as the emissions from producing electricity with the EU average mix are lower than those from fuel production. These values are based on the development of the EU grid mix as projected by the JRC's POTEnCIA CETO model. When considering the development of the grid mix according to the IEA's Stated Policy Scenario, which is indicated by the yellow error bars, BEVs showed higher emissions, of 70 g CO_2e/km, and PHEV emissions were 167 g CO_2e/km. When running solely on renewable electricity, BEVs reached life-cycle emissions of 52 g CO_2e/km, which is 78% lower than gasoline vehicles.

FCEVs driving solely on renewable electricity-based hydrogen also showed low life-cycle GHG emissions, of 50 g CO_2e/km—a decarbonization potential of 79%. When driving on natural gas-based hydrogen, however, the life-cycle GHG emissions of FCEVs were 175 g CO_2e/km, which is similar to the emissions of HEVs and PHEVs. This highlights that FCEVs only provide an emissions benefit comparable to BEVs when using solely renewable electricity-based hydrogen, which is currently not produced and available at scale in Europe. In contrast, BEVs show high emissions reduction potential already when driving on the average grid mix.

IMPACT OF KEY METHODOLOGICAL CHOICES

This section examines the variation in vehicle life-cycle emissions when key methodological considerations are changed.

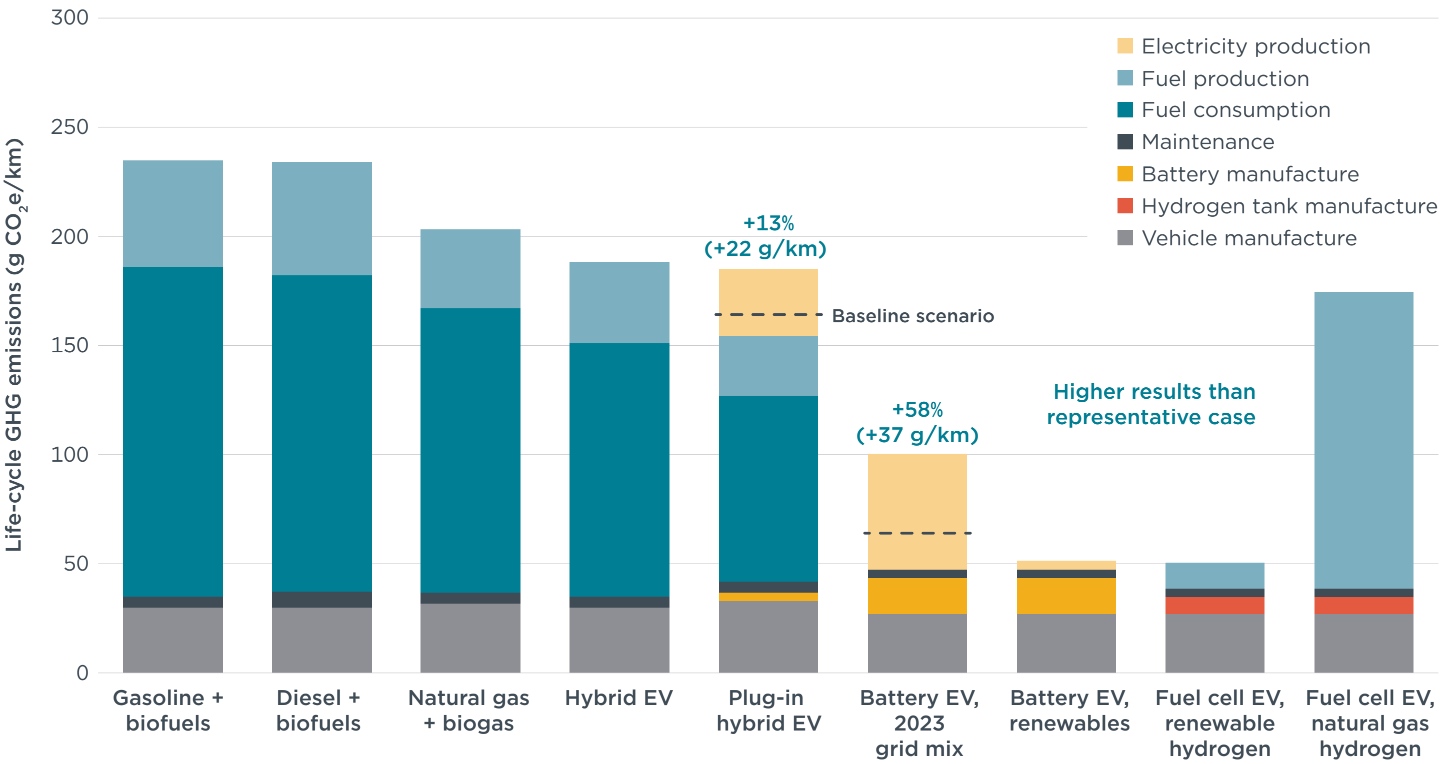
FACTOR 1: LIFETIME FUEL AND ELECTRICITY MIX

The expected development of the fuel and electricity mix was one of the most important factors for determining vehicles' life-cycle emissions. Figure 5 illustrates the life-cycle GHG emissions of the select vehicles considering that the historic electricity mix of 2023 would remain constant for the whole 2025–2044 vehicle lifetime. Using this static electricity mix overestimated the life-cycle emissions of BEVs by +58% (37 g CO_2e/km) when compared with accounting for expected changes. Similarly, but less pronounced, the life-cycle emissions of PHEVs were overestimated by +13% (22 g CO_2e/km).

Unlike for the development of the electricity mix, it is uncertain whether future policies will result in significant changes in the average gasoline, diesel, and natural gas blends. Further, as illustrated in the sensitivity scenario with very optimistic shares of advanced biofuels, changes in fuel composition have a minimal effect on vehicles' life-cycle emissions due to the relatively small proportion of biofuels in the overall fuel mix.

Figure 5

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025 using a static fuel and electricity mix



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FACTOR 2: REAL-WORLD FUEL AND ELECTRICITY CONSUMPTION

Using WLTP fuel and energy consumption values led to significantly lower estimated life-cycle emissions than using reported real-world consumption values. As illustrated in Figure 6, relying on WLTP instead of real-world data led to an underestimation of actual emissions across all powertrain types. This underestimation was particularly evident for vehicles with high usage phase emissions: ICEVs, HEVs, and grey hydrogen-powered FCEVs showed 23–33 g CO_2e/km (12%–16%) lower life-cycle GHG emission intensities than when using real-world consumption values.

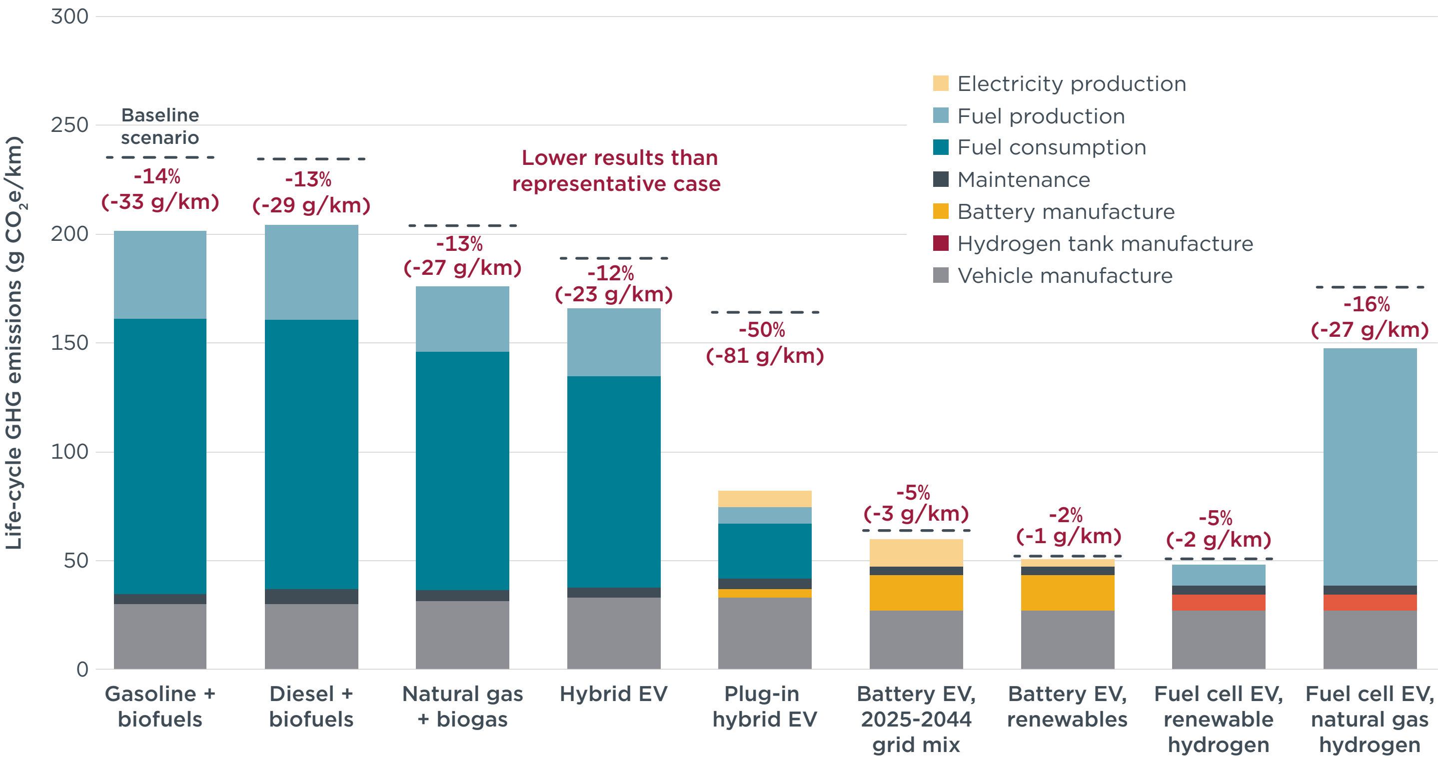
The most significant gap was observed among PHEVs, for which the WLTP values were 81 g CO_2e/km lower, resulting in an underestimation of their life-cycle GHG emissions by half (50%). In addition to the deviation from test cycles observed for all powertrain types, this substantial difference for PHEVs is primarily due to the fact that these vehicles are charged and driven less in CD mode than assumed in the type-approval values. As a result, the OBFCM data from PHEVs driven in the European Union are observed to exceed the WLTP fuel consumption figures by a factor of more than 3 (European Environment Agency, 2025b).

For BEVs, in contrast, the deviation between real-world and WLTP electricity consumption had a lower impact on life-cycle GHG emissions. Due to the overall lower impact of the usage phase for these vehicles, considering the WLTP values resulted in 3 g CO_2e/km (5%) lower life-cycle GHG emissions. The results for FCEVs running on green hydrogen were similar, with 2 g CO_2e/km (5%) lower life-cycle emissions when considering WLTP values.

Overall, the use of WLTP instead of real-world fuel consumption data tended to distort the comparative environmental performance of vehicle types, disproportionally favoring those with high emissions in the usage phase, in particular PHEVs.

Figure 6

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025 using WLTP energy consumption values



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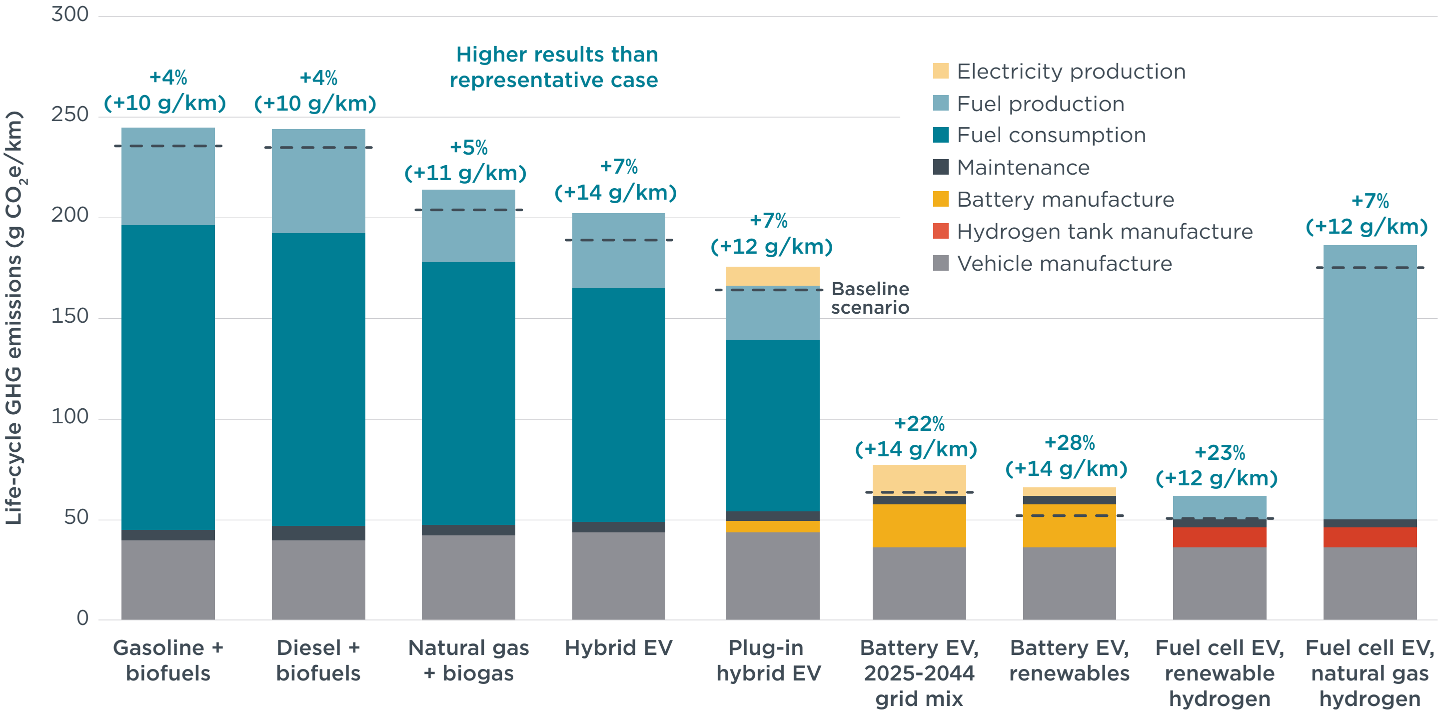
FACTOR 3: FULL VEHICLE LIFETIME

Using a shorter vehicle lifetime led to higher estimated emissions compared with using a full vehicle lifetime. As discussed in the methods section, the age of vehicles at the point of recycling has been increasing, with the latest evidence from EU Member States indicating an average lifetime of at least 20 years. Considering outdated values, or values that only refer to the time vehicles spend on the roads before being exported as used vehicles, could result in lower values. Figure 7 illustrates how assuming a vehicle lifetime of only 15 years affected the comparison of powertrain types relative to assuming a lifetime of 20 years. In both cases, an average annual mileage of 12,000 km was considered, resulting in a lifetime mileage of 180,000 km over 15 years and 240,000 km over 20 years.

Figure 7

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025 using a 15-year lifetime



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Assuming a lifetime of only 15 years, BEVs using the average electricity mix showed 22% (14 g CO_2e/km) higher emissions than when using a 20-year lifetime. For BEVs using renewable electricity, the emissions were 28% (14 g CO_2e /km) higher. Green hydrogen-powered FCEVs showed 23% (12 g CO_2e /km) higher emissions. For powertrain types with higher usage phase emissions, in contrast, the emissions increased to a more limited extent: by 4%–5% for gasoline, diesel, and CNG ICEVs and by 7% for HEVs, PHEVs, and grey hydrogen-powered FCEVs.

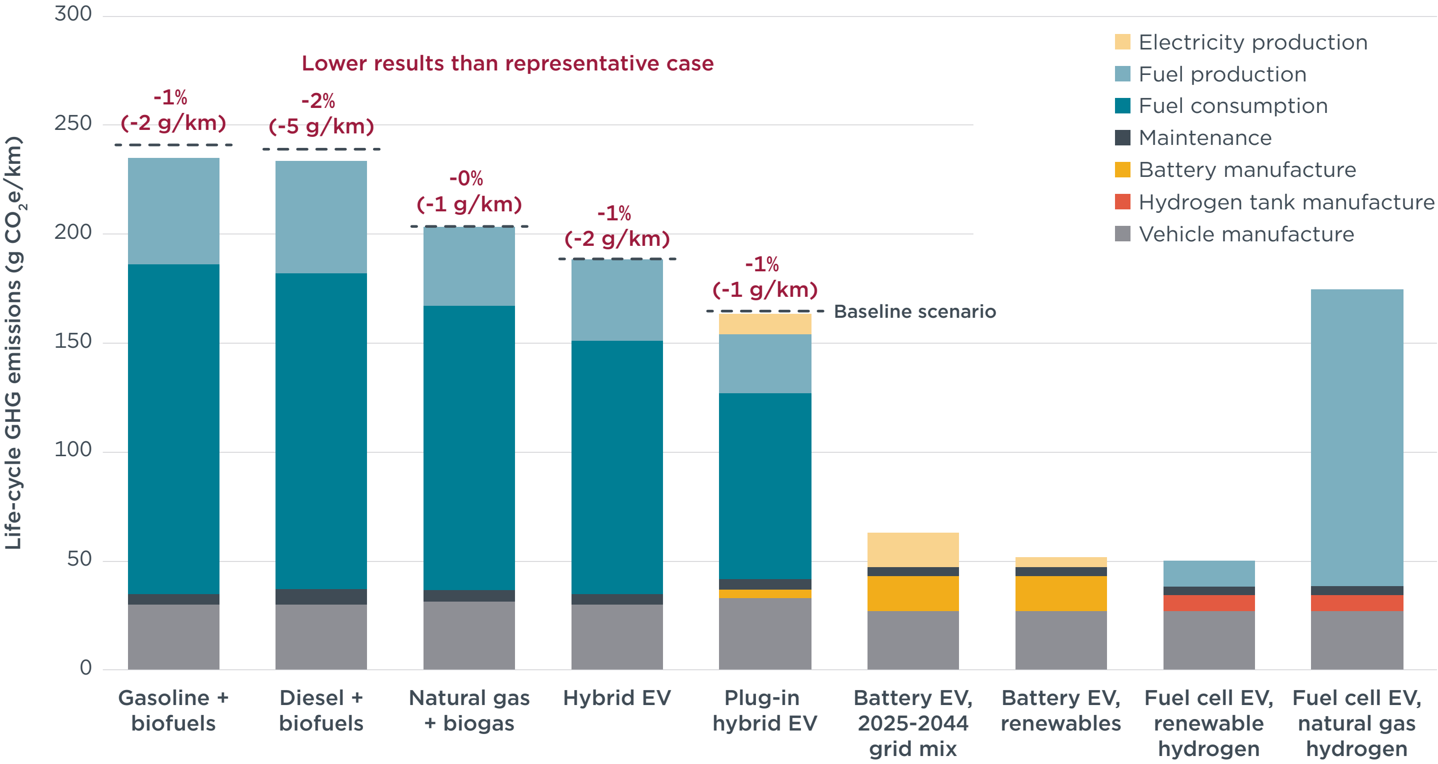
The results of this analysis are pronounced for BEVs for two reasons. First, as a larger proportion of BEVs' life-cycle emissions correspond to vehicle and battery production, a shorter assumed lifetime means that these production emissions are distributed over a lower mileage. Second, the life-cycle GHG emissions of BEVs decline with the use of a lower-emission intensity grid in the future; a shorter lifetime means that this potential is not fully realized. Disproportionately low lifetime assumptions thus overemphasize the impact of production emissions while undervaluing the long-term environmental benefits of electric vehicles.

FACTOR 4: INDIRECT LAND USE CHANGE EMISSIONS

As discussed in the methods section, ILUC emissions correspond to a larger share of the WTT emissions of conventional biofuels pathways, in particular for palm and soy oil-based biodiesel and HVO. Figure 8 shows the estimated impact of excluding these emissions. The impact is relatively limited, varying between -2% (-5 g CO_2e/km) for diesel ICEVs, -1% (1–2 g CO_2e/km) for gasoline-powered ICEVs, HEVs, and PHEVs, and less than 1% (1 g CO_2e/km) for CNG ICEVs. This limited impact is largely due to regulatory measures in the European Union that restrict food and feed biofuels or exclude the use of biofuels designated as "high ILUC," and by a comparatively low biofuels share in the overall EU gasoline, diesel, and CNG blends.

Figure 8

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025 without including ILUC emissions



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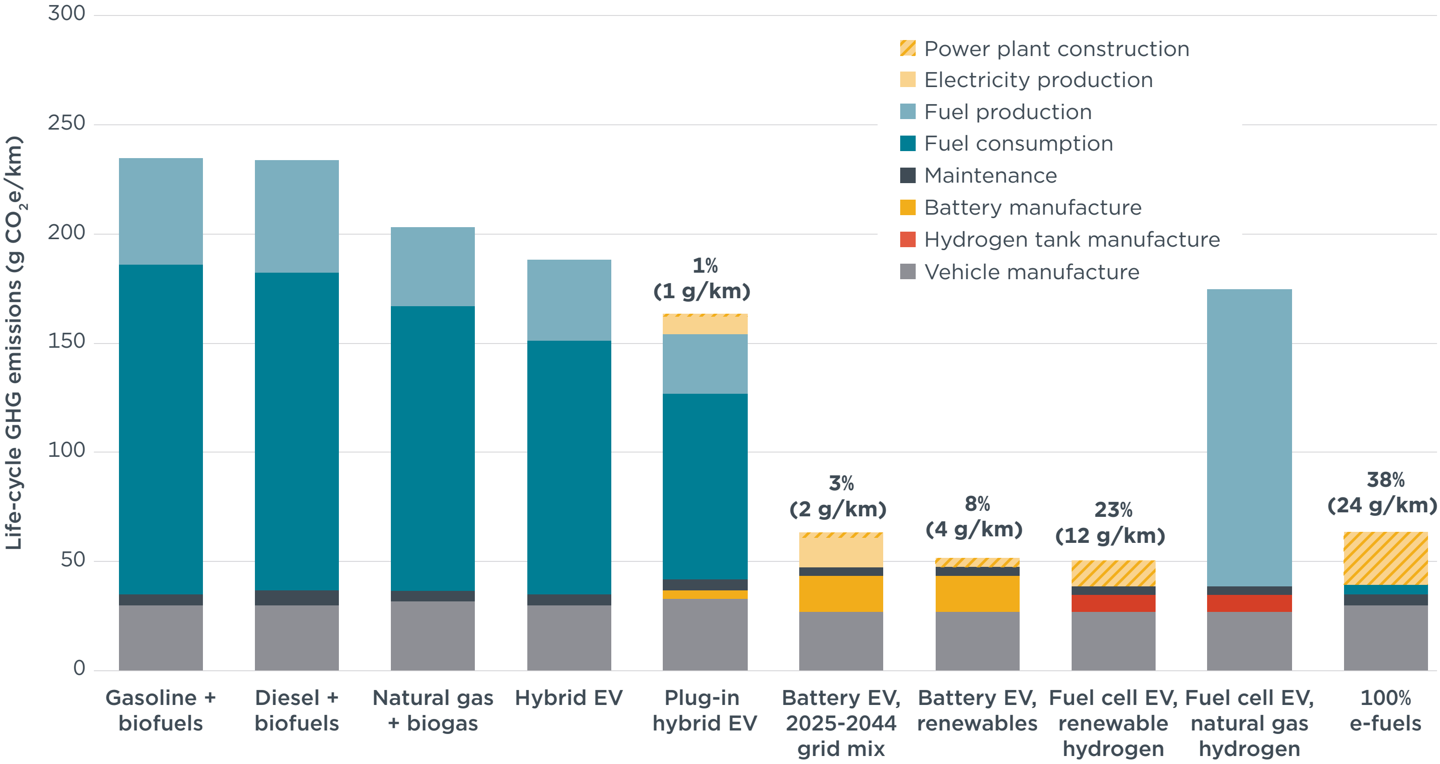
In regions where the share of biofuels in the fuel mix is higher—such as Brazil (Mera et al., 2023)—or where high ILUC-risk feedstocks are more prevalent—such as Indonesia (Mera & Bieker, 2023)—the impact of ILUC on vehicle life-cycle emissions can correspond to up to a third of the overall life-cycle GHG emissions of vehicles.

FACTOR 5: ELECTRICITY GENERATION INFRASTRUCTURE EMISSIONS

Figure 9 displays the impact of emissions related to generation infrastructure for the electricity used in the usage phase. These emissions (which cover, for example, the production of solar panels or wind power plants) can represent a large share of the life-cycle emissions of electricity generation. Given the high relative share of these emissions in the life-cycle emissions intensity of renewables (see Table 5), their inclusion in the analysis would mainly affect the emissions intensity of using renewable electricity. In addition to green hydrogen-powered FCEVs, the figure thus also displays the hypothetical case of an ICEV solely run on e-fuels.

Figure 9

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025, highlighting the impact of electricity generation infrastructure emissions relative to baseline assumptions



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For the hypothetical case of a vehicle solely fueled with e-fuels, electricity generation infrastructure emissions accounted for 24 g CO_2e /km (38%) of the overall life-cycle emissions. Similarly, for FCEVs using green hydrogen, electricity generation infrastructure emissions accounted for 12 g CO_2e /km (23%) of life-cycle emissions. For comparison, for renewable electricity used in BEVs, these emissions accounted for only 4 g CO_2e/km (8%) of total life-cycle emissions. BEVs and PHEVs using the average electricity mix were hardly affected, with electricity generation infrastructure emissions accounting for 2–1 g CO_2e /km (3%–1%) of total life-cycle emissions.

The varying impacts of electricity generation infrastructure-related emissions for BEVs, green hydrogen FCEVs, and e-fuel-powered ICEVs relates to the energy losses—and thus overall electric energy consumption—of these pathways. Given energy losses during electrolysis, hydrogen compression, and dispensing at the retail site, as well as processing in the fuel cell, green hydrogen FCEVs demand about 3 times the amount of renewable electricity than is used in BEVs (including charging losses). For e-fuels, the energy losses during electrolysis, CO_2 capturing, fuel synthesis, and fuel combustion results in an electric energy consumption about 6 times higher than the direct use of electricity in BEVs (Bieker, 2021).

SUMMARY AND CONCLUSIONS

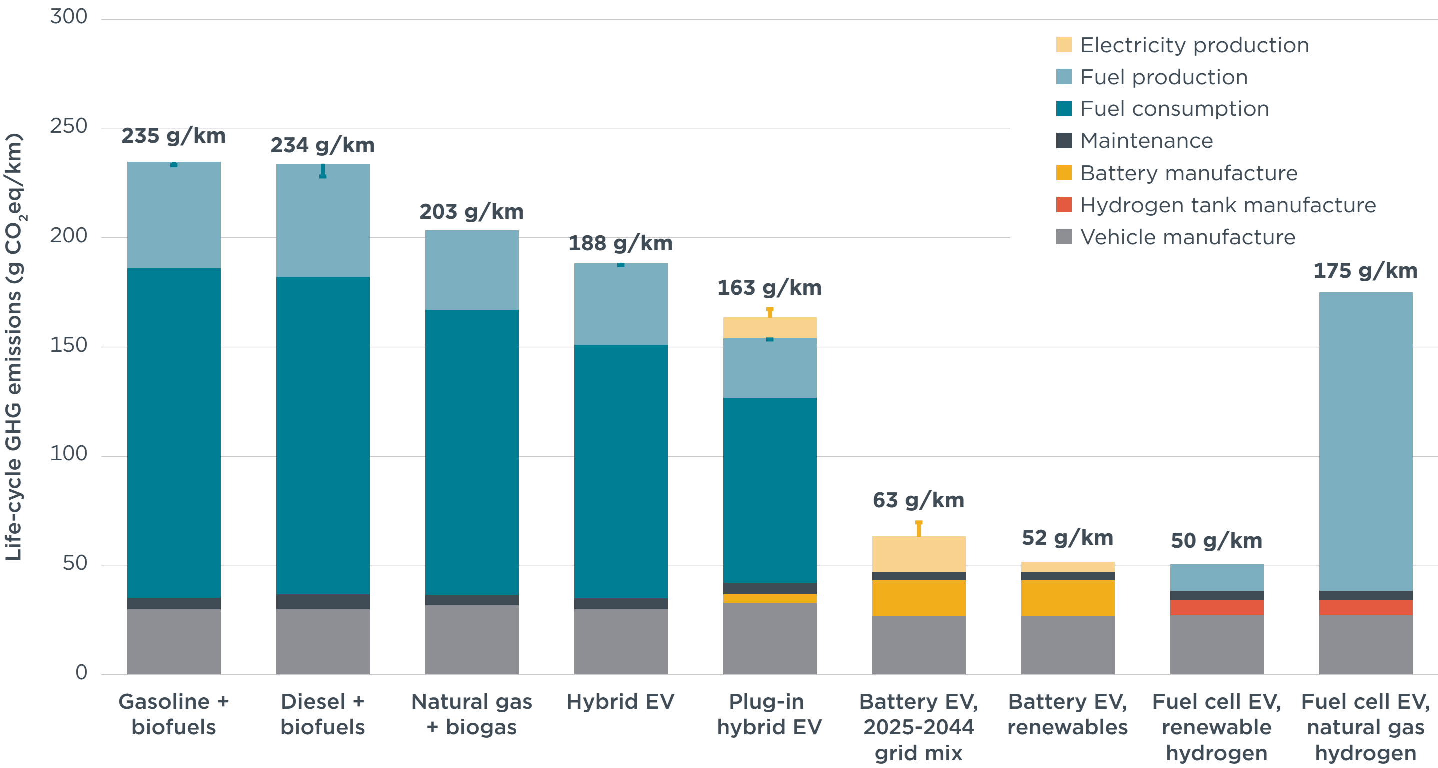
This report assessed the life-cycle GHG emissions of vehicles in the European Union using a set of baseline parameters based on real-world data to allow a representative and comprehensive comparison across powertrains. Further, it examined how changing key methodological factors affected the results.

Updating a previous ICCT study (Bieker, 2021), this report found that, in the baseline case for vehicles sold in 2025, BEVs running on the average electricity mix had estimated life-cycle GHG emissions of 63 g CO_2e/km, 73% lower than gasoline ICEVs. When running solely on renewable electricity, BEVs reached life-cycle emissions of 52 g CO_2e/km, 78% lower than gasoline vehicles. FCEVs powered solely with renewable electricity-based hydrogen also showed low estimated life-cycle GHG emissions, of 50 g CO_2e/km—a decarbonization potential of 79% compared with gasoline vehicles. When driving on natural gas-based hydrogen, however, the life-cycle GHG emissions of FCEVs reached 175 g CO_2e/km. This highlights that FCEVs provide an emissions benefit comparable to BEVs only when using renewable electricity-based hydrogen, while BEVs show a greater emissions reduction potential when driving on the average grid mix.

In contrast, ICEVs running on the average gasoline and diesel mix showed similarly high estimated life-cycle GHG emissions, of 235 g CO_2e/km and 234 g CO_2e/km, respectively. Natural gas-powered ICEVs, meanwhile, had life-cycle emissions of 203 g CO_2e/km, 13% lower than gasoline ICEVs. HEVs and PHEVs had similar estimated life-cycle GHG emissions, of 188 g CO_2e/km and 163 g CO_2e/km, respectively, 20%–30% lower than the conventional gasoline ICEV comparator. These results indicate that hybridization does offer life-cycle GHG emission benefits relative to conventional ICEVs, but that this benefit is relatively small compared with the emissions reduction potential of BEVs or renewable hydrogen-based FCEVs.

Figure 10

Life-cycle GHG emissions of medium vehicles in the European Union in 2025 in the baseline case



Notes: The yellow error bars indicate the difference between the development of the electricity mix according to the JRC's (2024) POTEnCIA CETO 2024 scenario (our baseline case) and the IEA's (2024b) Stated Policy Scenario. The blue error bars compare the RED III compatible fuel mix scenario (our baseline case) with a hypothetical scenario of largely increased advanced biofuels shares.

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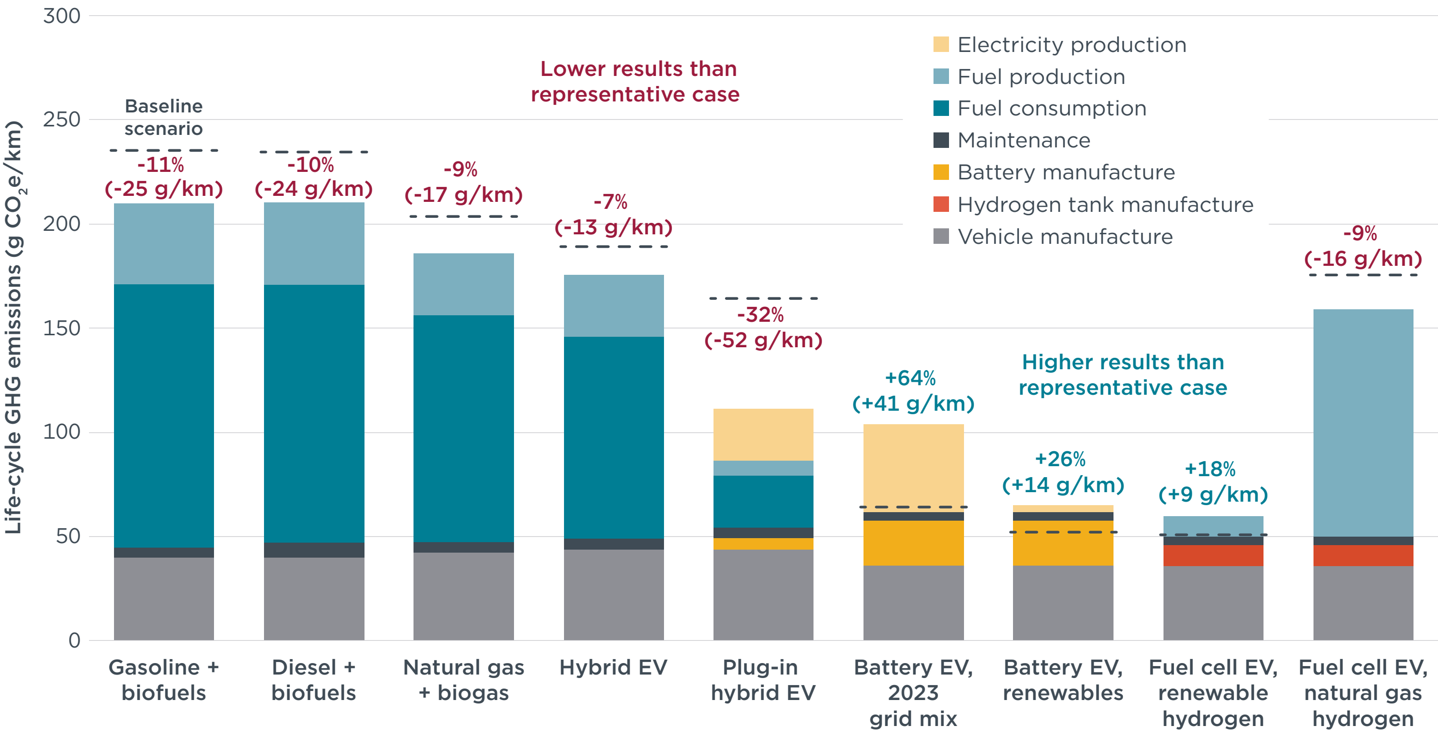
This report also evaluated the impact of changes in five methodological factors on the outcome of the LCA: 1) neglecting the expected decarbonization of the electricity mix during the vehicles' lifetime; 2) using official test cycle instead of representative real-world energy consumption data; 3) underestimating a full vehicle lifetime; 4) not accounting for ILUC emissions; and 5) excluding electricity generation infrastructure emissions. Figure 11 illustrates the combined effect of not including factors 1 through 4 in the analysis.

Figure 11

Life-cycle GHG emissions of medium vehicles sold in the European Union in 2025 using static fuel and electricity mixes, WLTP fuel and electricity consumption data, a 15-year vehicle lifetime, and excluding ILUC emissions



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Most notably, the life-cycle emissions of BEVs can appear up to 64% higher when these factors are not accounted for with representative values. Under such conditions, BEVs appear to have emissions levels comparable to PHEVs, whose life-cycle emissions are themselves underestimated by around 32% when based on non-representative assumptions. This demonstrates how sensitive LCA results are to key assumptions. Without consideration representative values for each of these factors, comparative assessments risk drawing misleading conclusions. Following the best practices we outlined in the baseline case best captures the relative emissions performance of the different powertrains.

POLICY CONSIDERATIONS

Our LCA results indicate that maintaining the phaseout of new sales of combustion engine cars and all types of hybrids by 2035 would accelerate the decarbonization of the transport sector in the European Union. The life-cycle GHG emissions of BEVs sold today are estimated to be 73% lower than for comparable gasoline- and diesel-powered ICEVs, while HEVs and PHEVs only enable a reduction of 20%–30%. Additionally, FCEVs have the potential to reduce life-cycle GHG emissions by 79%, but only if they are powered by renewable electricity-based hydrogen.

In parallel with tailpipe CO_2 emission standards and a phaseout of combustion engine vehicles, complementary policies can help to decarbonize vehicles throughout their other life-cycle stages. Production emissions can be addressed by introducing maximum production emission thresholds and by minimum recycled content mandates as foreseen for batteries in the EU Battery Regulation. On a vehicle level, recycled content mandates are under consideration for plastic, aluminum, and steel in the European Commission's proposal for a regulation on circularity requirements for vehicle design and on management of end-of-life vehicles. Quotas could also be introduced for low-carbon materials used in vehicle production, such as green steel. Improvements in the energy efficiency of BEVs could be achieved through energy efficiency standards.

Decarbonization of the electricity mix can maximize the GHG emissions benefit of BEVs. Policies to decarbonize the European Union's power sector include the EU ETS, which covers the emissions from electricity generation and promotes the installation of new renewable electricity capacity.

Regulations based on LCAs could also be an approach in the long term (e.g., post-2035), in addition to the current tailpipe emissions CO_2 standards and the phaseout of ICEVs, HEVs, and PHEVs by 2035, but such regulations can present several challenges. For example, LCA-based regulations would require significant administrative efforts for companies to trace and report emissions for each step of vehicle production and for regulators to validate these data. They would also require time for building capacities and effective cross-industry data sharing platforms. Further, introducing LCA-based regulations would require establishing a baseline and a threshold curve that decreases over time. This would require years of data collection and efforts to develop a methodology to allow harmonized reporting of LCA emissions.

Finally, this study indicates that several factors and assumptions have an important influence on the life-cycle GHG emission estimates of vehicles, resulting in substantial variation across different vehicle technologies. For a representative and comprehensive comparison of the climate impact of powertrain types, the following factors should be considered in the LCA methodology:

» Electricity and fuel mix assumptions should reflect the expected decarbonization of energy systems in the European Union over a vehicle's lifetime. Not accounting for these changes results in a significant overestimation of emissions, particularly for BEVs, the emissions of which depend greatly on the electricity mix considered.

» Real-world fuel and electricity consumption data offer a better representation of consumption than official test-cycle (e.g., WLTP) values, which often underestimate actual usage. As shown in our analysis, the use of test values can underestimate the life-cycle emissions of PHEVs by 50%, thus resulting in an unrealistic comparison with other powertrains.

» Using an average operational vehicle lifetime of 20 years as observed in vehicle recycling statistics, as opposed to the average age at which a vehicle is deregistered (which includes vehicles that are only exported and continue to be used in other markets), captures the life-cycle emissions best. This is particularly important for a comparison with BEVs, as the higher production emissions are compensated for during vehicle operation and the longer lifetime allows BEVs to benefit more from the improvements in the electricity mix.

» Indirect land-use change emissions make up a significant share of the life-cycle emissions of biofuels. Accounting for ILUC would more accurately reflect a vehicle's life-cycle emissions and is particularly relevant in regions with high biofuel use or with a large share of biofuels made with feedstocks associated with high ILUC emissions.

» Accounting for the climate impact of electricity generation infrastructure emissions is especially relevant for powertrain types with a high consumption of renewable electricity, such as green hydrogen FCEVs and a hypothetical case of vehicles running entirely on e-fuels.

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