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A GLOBAL COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS

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EXECUTIVE SUMMARY

If the transportation sector is to align with efforts supporting the best chance of achieving the Paris Agreement's goal of limiting global warming to below 2 °C, the greenhouse gas (GHG) emissions from global road transport in 2050 need to be dramatically lower than today's levels. ICCT's projections show that efforts in line with limiting warming to 1.5 °C mean reducing emissions from the combustion and production of fuels and electricity for transport by at least 80% from today's levels by 2050, and the largest part of this reduction needs to come from passenger cars. Considering the expected future growth of the transport sector, the change needed on a per-vehicle basis will be even higher.

As important as it is to reduce the emissions from fuel and electricity production and consumption, such reduction should of course not come at the cost of higher vehicle production emissions. Taking all together, it is therefore important for policymakers to understand which powertrain and fuel technologies are most capable of shrinking the carbon footprint of cars—and not only the emissions from the tailpipes, but also from fuel and electricity production and vehicle manufacturing.

This study is a life-cycle assessment (LCA) of the GHG emissions of passenger cars in China, Europe, India, and the United States, four markets that are home to the majority of global new passenger car sales and reflect much of the variety in the global vehicle market. The study considers the most relevant powertrain types—internal combustion engine vehicles (ICEVs), including hybrid electric vehicles (HEVs); plug-in hybrid electric vehicles (PHEVs); battery electric vehicles (BEVs); and fuel cell electric vehicles (FCEVs)—and a variety of fuel types and power sources including gasoline, diesel, natural gas, biofuels, e-fuels, hydrogen, and electricity. For each region, the analysis is based on average vehicle characteristics across the most representative market segments and considers fuel and electricity consumption in real-world driving conditions. Additionally, based on stated policies, the study estimates how the life-cycle GHG emissions of cars expected to be registered in 2030 compare with vehicles registered today. For both 2021 and 2030 cars, it considers the changing fuel and electricity mixes during the lifetime of the vehicles.

Key results include the following:

Only battery electric and hydrogen fuel cell electric vehicles have the potential to achieve the magnitude of life-cycle GHG emissions reductions needed to meet Paris Agreement goals.

As shown for average new medium-size cars in Figure ES.1, the assessment finds that the life-cycle emissions over the lifetime of BEVs registered today in Europe, the United States, China, and India are already lower than a comparable gasoline car by 66%–69% in Europe, 60%–68% in the United States, 37%–45% in China, and 19%–34% in India. For medium-size cars projected to be registered in 2030, as the electricity mix continues to decarbonize, the life-cycle emissions gap between BEVs and gasoline vehicles increases to 74%–77% in Europe, 62%–76% in the United States, 48%–64% in China, and 30%–56% in India. As indicated in the figure, a large uncertainty lies in how the future electricity mix develops in each region; the high ends of the error bars reflect more emissions when only considering currently existing and announced policies, and the low ends reflect the implementation of policies the International Energy Agency projects would be required for the power sector to align with Paris Agreement targets.

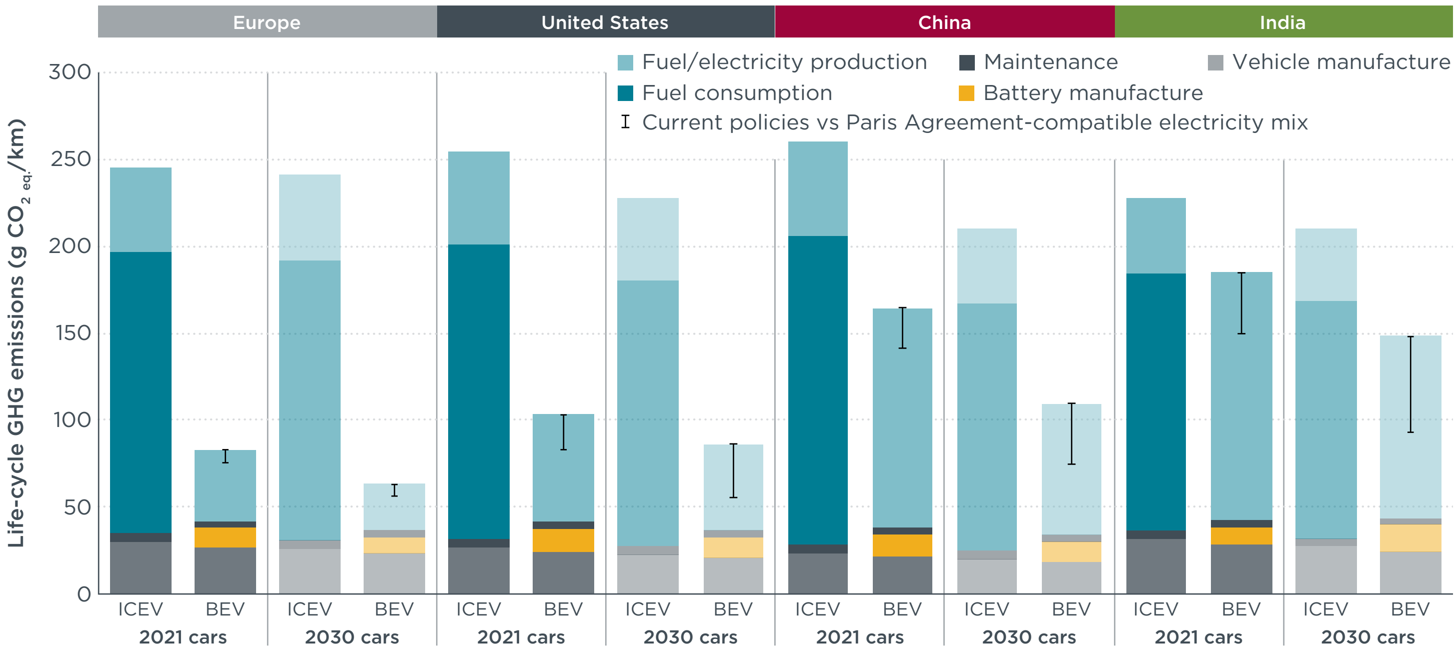

Figure ES.1. Life-cycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030. The error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement.

While BEVs registered today already produce significantly lower life-cycle GHG emissions on average, the same is not true for FCEVs fueled by hydrogen. This is because the primary source of hydrogen today is through reforming methane from natural gas ("grey hydrogen"), and that results in more modest life-cycle emissions reductions that are about 26%–40% less than for today's average medium-size gasoline vehicles in the respective regions. Utilizing hydrogen produced from renewable electricity ("green hydrogen"), instead, would result in 76%–80% lower life-cycle GHG emissions for FCEVs. Renewable energy powered FCEVs show slightly higher life-cycle emissions than BEVs powered by the same renewable electricity, though; this is because the electricity-based FCEV pathway is approximately three times as energy intensive as the BEV pathway, and as such, we took account of emissions from the construction of additional renewable electricity installations.

There is no realistic pathway for deep decarbonization of combustion engine vehicles. HEVs improve the efficiency of internal combustion engine vehicles by recovering braking energy and storing it in a battery that can then be used to support propulsion with an electric motor. In this study, HEVs are found to reduce life-cycle GHG emissions by only about 20% compared to conventional gasoline cars.

PHEVs have a larger battery that can be charged before driving and they can operate in a predominantly electric mode for a certain range. Also in this drive mode, though, the electric motor is usually supported by the combustion engine, and thus it is not necessarily purely electric driving. In any case, the life-cycle GHG emissions of PHEVs are mostly determined by the electric versus combustion engine drive share in average real-world usage. This is found to vary significantly between regions, and the life-cycle GHG emissions of today's medium-size PHEVs compared to gasoline cars is 42%–46% lower in the United States, 25%–27% lower in Europe, and 6%–12% lower in China, depending on the development of the electricity mix. (PHEVs are hardly registered in India.) Compared to average BEVs in the United States, Europe, and China, the life-cycle GHG emissions for PHEVs are 43%–64%, 123%–138%, and 39%–58% higher for cars registered in 2021 and 53%–100%, 171%–197%, and 94%–166% higher for cars expected to be registered in 2030.

This study also analyzed the development of the average blend of biofuels and biogas in fossil diesel, gasoline, and natural gas based on current policies and projected supply. Across the four regions and all fuel types, the impact of future changes in the biofuel blends driven by current policies range from a negligible influence to a reduction of the life-cycle GHG emissions of gasoline, diesel, or natural gas vehicles by a maximum of 9%, even over the lifetime of cars registered in 2030. Due to a number of factors, including competing demand from other sectors and high cost of production, it is not feasible to supply enough low-carbon biofuels such as residues- and waste-based biodiesel, ethanol, or biomethane to substantially displace fossil fuels in combustion engine cars. Additionally, the very high production cost of e-fuels means they are not likely to contribute substantially to decarbonization of the fuel mix within the lifetimes of 2021 or 2030 cars.

To align with Paris Agreement targets, the registration of new combustion engine vehicles should be phased out in the 2030–2035 time frame. Given average vehicle lifetimes of 15–18 years in the markets analyzed and that Paris Agreement reduction targets need to be met by 2050, only those technologies that can achieve a deep decarbonization should be produced and registered by about 2030–2035. Based on the assessment presented here, BEVs powered by renewable electricity and FCEVs fueled by green hydrogen are the only two technology pathways that qualify. Hybridization can be utilized to reduce the fuel consumption of new internal combustion engine vehicles registered over the next decade, but neither HEVs nor PHEVs provide the magnitude of reduction in GHG emissions needed in the long term. Thus, the registration of new cars with these powertrain types needs to be phased out in the 2030–2035 time frame.

In the meantime, given the life-cycle GHG emission benefits that BEVs already provide today, the transition to electric cars need not wait for future power sector improvements. Indeed, the benefits of a continuously decarbonizing power sector can only be captured in full if the transition to electric vehicles proceeds well ahead of that.

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LIST OF ACRONYMS

ADAC	Allgemeiner Deutscher Automobil-Club
BEV	Battery electric vehicle
CCS	Carbon capture and storage
CH_4	Methane
CLTC	China light-duty vehicle test cycle
CNG	Compressed natural gas
CO_2	Carbon dioxide
$CO_{2\ eq.}$	Carbon dioxide equivalent
EDF	Environmental Defense Fund
EPA	United States Environmental Protection Agency
FAME	Fatty acid methyl ester
FCEV	Fuel cell electric vehicle
GWP	Global warming potential
HEV	Hybrid electric vehicle
HVO	Hydrogenated vegetable oil
IEA	International Energy Agency
JRC	Joint Research Center (European Commission)
GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
ILUC	Indirect land use change
LCA	Life-cycle assessment
LNG	Liquefied natural gas
MIDC	Modified Indian Driving Cycle
MSW	Municipal solid waste
N_2O	Nitrous oxide
NCA	Lithium nickel cobalt aluminum oxide
NEDC	New European Driving Cycle
NEV	New energy vehicles
NMC	Lithium nickel manganese cobalt oxide
PHEV	Plug-in hybrid electric vehicle
SDS	Sustainable Development Scenario
STEPS	Stated Policy Scenario
SUV	Sport utility vehicle
TTW	Tank to wheel
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WTT	Well to tank
WTW	Well to wheel
ZEV	Zero-emission vehicle
ZLEV	Zero- and low-emission vehicle

1 INTRODUCTION

On a global scale, the production and combustion of fuels in the transportation sector currently results in the emission of approximately 12 Gt of CO_2 equivalent ($CO_{2\ eq.}$) into the air per year, and this is about 25% of all anthropogenic greenhouse gas (GHG) emissions. With projected population and economic growth, global transportation demand is expected to increase substantially. Without further policy action, transport sector GHG emissions from combustion and production of fuels and electricity are expected to almost double to 21 Gt $CO_{2\ eq.}$ annually by 2050. However, supporting efforts in line with the best chances of limiting global warming to 1.5 °C means reducing these emissions by approximately 80% from today's levels, to a level of about 2.6 Gt $CO_{2\ eq.}$ per year by 2050 (International Council on Clean Transportation, 2020).

Light-duty vehicles, the vast majority of which are passenger cars, are responsible for the largest share of transport-related GHG emissions, currently about 5 Gt $CO_{2\ eq.}$ (International Council on Clean Transportation, 2020). To reduce the GHG emissions of light-duty vehicles, many governments follow two complementary approaches: (1) They aim to reduce the fuel consumption of new vehicles by setting fleet average CO_2 emission or fuel efficiency standards, and by providing incentives for vehicles with electric powertrains; and (2) They support the decarbonization of the electricity grid and incentivize the production of renewable and low-carbon fuels.

In this context, this study evaluates a variety of powertrain and fuel technology pathways to identify which allow for deep reductions in the GHG emissions of the global passenger car fleet. It follows a life-cycle assessment (LCA) approach and considers the GHG emissions corresponding to fuel and electricity production, as well as the production, maintenance, and recycling of passenger cars in Europe (the European Union and United Kingdom), the United States, China, and India. These four regions accounted for about 70% of global new car sales in 2019 (European Automobile Manufacturers Association, 2020) and are reflective of much of the variety in the global passenger car market.

The life-cycle GHG emissions of gasoline, diesel, and natural gas powered internal combustion engine vehicles (ICEVs), which include hybrid electric vehicles (HEVs), are compared to the emissions of plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). For each of the four regions, the study considers the life-cycle GHG emissions impact of biofuels under both current and future blending rates, future changes in the average electricity grid mixes, and the life-cycle GHG emissions of various pathways of producing hydrogen fuel. To understand the future potential of the different powertrain types, the GHG emissions over the lifetime of cars registered in 2021 are compared with those of the cars expected to be registered in 2030.

In addition to its **regional** and **temporal scope**, this study is distinct from earlier LCA literature in four key aspects:

» This study considers the lifetime average carbon intensity of the fuel and electricity mixes, including biofuels and biogas. Based on stated policies, it accounts for changes in the carbon intensity during the useful lifetime of the vehicles.

» This study considers the fuel and electricity consumption in **average real-world** usage instead of solely relying on official test values. This is especially important for assessing the GHG emissions of PHEVs.

» This study uses recent data on industrial-scale battery production and considers regional battery supply chains. This results in significantly **lower battery production emissions** than in earlier studies.

» This study incorporates the near-term global warming potential of **methane leakage** emissions of natural gas and natural gas-derived hydrogen pathways. Different from other GHGs, methane contributes several times more to global warming in the first 20 years after emission than is reflected by the 100-year global warming potential (GWP).

In Section 2, the scope and methodology of this study is described in general terms, and there is additional, particular focus on the assessment of the battery production emissions, the lifetime average electricity mix, and the 20-year GWP of methane emissions. Full details of the considered data and assumptions for these and the remainder of the analysis are provided in the Appendix.

2 METHODOLOGY

2.1 APPROACH AND SCOPE

This LCA generally follows an attributional approach and thereby considers the average GHG emissions that can be attributed to the vehicle and fuel pathways over their lifetime. Some values, like the indirect land use change emissions of biofuel production, are captured by a consequential approach. As such, those values reflect the changes the production causes in the broader economy.

The overarching goal of this work is to identify the powertrain technologies that allow a deep reduction of the 100-year GWP (in $CO_{2\ eq.}$) of passenger cars within the existing or planned policy frameworks, and 100-year GWP is dominant in the literature. For methane emissions, which mostly occur during natural gas production and transport, the 20-year GWP is several times higher than the 100-year GWP, however, and this is different from the other GHGs considered. To account for that, the study also estimates the 20-year GWP of methane emissions for natural gas and natural gas-derived hydrogen.

Four regions are assessed—Europe (the European Union and United Kingdom), the United States, China, and India—and the study considers the life-cycle GHG emissions of gasoline, diesel, and compressed natural gas (CNG) powered ICEVs, PHEVs, BEVs, and FCEVs, whichever powertrains are used in the given region. The powertrain types are compared using sales-weighted average characteristics across the most representative market segments. The fuel and electricity consumption values correspond to real-world driving conditions, and except for hydrogen, the study considers average electricity and fuel mixes. On a temporal scale, the study assesses the life-cycle GHG emissions of cars registered in 2021 and compares them with estimations of cars expected to be registered in 2030. Changes in the average carbon intensity of the fuel and electricity mix during the lifetime of the 2021 and 2030 cars are based on stated policies.

The GHG emissions of vehicle production, maintenance, and recycling (i.e., vehicle cycle) and fuel and electricity production and consumption (i.e., fuel cycle) are combined into a single value based on the functional unit of g $CO_{2\ eq.}$/km traveled. As listed in Tables 2.1 and 2.2 and described in Sections 2.2 and 2.3, the analysis includes all direct and indirect GHG emissions with a significant influence on the total life-cycle GHG emissions of the different powertrains. Meanwhile, emissions corresponding to the construction and maintaining of the infrastructure for vehicle production and recycling, fuel transport and distribution, and vehicle charging, and emissions corresponding to road infrastructure, are not considered, as these are similar for the different powertrain types or have only a small influence on total life-cycle GHG emissions.

2.2 VEHICLE CYCLE

The vehicle cycle considers the GHG emissions of vehicle production, maintenance, and recycling (“cradle to grave”). Vehicle production and recycling (where applicable) are considered with respect to three categories of components: the battery of BEVs and PHEVs, the hydrogen system of FCEVs, and the rest of the vehicle, which is denoted as glider and powertrain. This separate estimation of the GHG emissions of the battery and the hydrogen system is important because the GHG emissions of the rest of the vehicle are relatively powertrain-type agnostic. Table 2.1 summarizes the boundaries of the GHG emissions considered in the vehicle cycle, including those corresponding to the maintenance during the use phase of the vehicles. With the region-specific lifetime mileage, the GHG emissions corresponding to the glider and powertrain, the battery, and the hydrogen system are translated into the functional unit of g $CO_{2\ eq.}$/km traveled. While the battery production GHG emissions are further discussed in Section 2.4, details regarding the glider and powertrain, hydrogen system, and lifetime mileage are provided in **Section A.1** of the Appendix.

Table 2.1. Scope of GHG emissions considered in the vehicle cycle.

Glider and powertrain	• Production of the vehicle, including raw material extraction and processing, component manufacture, and assembly • Recycling of vehicle components, time-sensitive hybrid of avoided burden and cut-off approach
Battery	• Production of the battery packs, including extracting and processing of raw materials, cell production, and pack assembly • *Not included*: second-life use and recycling
Hydrogen system	• Production of the hydrogen tank and fuel cell, including raw material extraction and processing, and component manufacture • *Not included*: component recycling/disposal
Maintenance	• In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, urea, and others

Glider and powertrain

The GHG emissions of the production and recycling of the vehicles' glider and powertrain are based on powertrain type-specific factors (in t $CO_{2\ eq.}$/t vehicle) and the segment-specific average weight of cars registered in the analyzed regions in 2019. With a continuous decarbonization of the economy, these GHG emission factors are assumed to be lower in 2030. Vehicle weight is assumed to remain constant.

Battery

The production of the battery in BEVs and PHEVs is calculated with regionally and temporally adjusted carbon intensity factors (in kg $CO_{2\ eq.}$/kWh) and battery capacities (in kWh). For cars registered in 2021, the GHG emission factors of the battery production are based on the most common battery chemistry, NMC622-graphite batteries, and the regional mix of batteries produced in or imported from Europe, the United States, China, South Korea, and Japan in 2019. For cars expected to be registered in 2030, these factors correspond to NMC811-graphite batteries that are produced domestically in the regions examined in this study. The battery capacities considered for BEVs in 2021 are the segment-specific market averages in 2019, and for PHEVs, they correspond to representative models. With the expected decrease in battery costs, the capacities of BEV and PHEV batteries are assumed to be higher in 2030.

Battery recycling is likely to significantly reduce the GHG emissions impact of batteries. Due to uncertainty regarding future recycling processes, however, the corresponding GHG emission credits are not included in this assessment. Similarly, the reduced GHG emissions impact of use of vehicle batteries in second-life applications is discussed, but due to the uncertainty of the battery lifetime, it is not considered. In any case, the batteries are assumed to last longer than the vehicles' lifetime (Harlow et al., 2019), so they do not need to be replaced.

Hydrogen system

The GHG emissions corresponding to the hydrogen tank and fuel cell in FCEVs vary with the capacity of the hydrogen tank and mostly come from the energy-intensive production of carbon fiber reinforced plastic for the hydrogen tank. Same as what is assumed for the batteries of BEVs and PHEVs, hydrogen systems are assumed to be producible with 20% lower GHG emissions in 2030. As materials from carbon fiber reinforced plastic are currently incinerated or disposed as landfill, the recycling of hydrogen tanks is not considered in this analysis. With recycling processes currently being developed (Karuppannan Gopalraj & Kärki, 2020), though, the GHG emissions of the hydrogen system might be reduced in the future.

Maintenance

During the use phase of the vehicles, the replacement of vehicle components like tires and parts of the exhaust/aftertreatment system, and of consumables like coolant, oil, and urea, correspond to GHG emissions. Since they require only some of these materials, BEVs and FCEVs correspond to slightly lower maintenance GHG emissions than ICEVs and PHEVs.

Lifetime mileage

The lifetime mileages used in this analysis were based on the average lifetime of vehicles registered in the investigated regions in 2021 and expected to be registered in 2030, in combination with annual mileage per vehicle age curves and average annual mileage data. The values are adjusted to the respective regions and vehicle segments but are considered to be the same for all powertrain types. The vehicles are considered to be used in the respective regions for their full useful life, with no consideration of their potential export as second-hand cars to other regions.

2.3 FUEL CYCLE

The GHG emissions from the fuel and electricity consumed during driving are considered in the fuel cycle. These include the GHG emissions from the production of the fuel and electricity ("well to tank," or WTT) and the fuel consumption in the vehicle ("tank to wheel," TTW).

The following sections describe how representative, real-world fuel and electricity consumption values were determined. They also detail the methodology and scope of the WTT and TTW GHG emissions of the fossil and renewable fuel feedstocks considered in the average gasoline, diesel, and natural gas blends in Europe, the United States, China, and India, and how the life-cycle GHG emissions corresponding to the electricity consumed in BEVs and PHEVs, and the production of hydrogen and liquid e-fuels, were assessed. Table 2.2 is an overview of the scope of the GHG emissions considered for the different fuels and electricity, and full details of the data used and assumptions are in **Section A.2** of the Appendix.

Table 2.2. Scope of the GHG emissions considered in the fuel cycle.

Fossil fuels	• Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution, all including methane leakage • CO_2, methane, and nitrous oxide (N_2O) emissions of fuel consumption
Biofuels	• Plant cultivation/waste collection, processing, and transport; and from fuel production and distribution • Indirect land use change GHG emissions of plant cultivation • Methane and N_2O emissions of fuel consumption
Electricity	• GHG emissions of electricity generation, including new power plant infrastructure for renewable energy, transmission, distribution, and charging losses
Hydrogen	• For electrolysis-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression • For 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 • *Not included*: long-distance hydrogen transport
E-fuels	• GHG emissions of electricity, adjusted by energy losses during electrolysis and fuel synthesis • *Not included*: long-distance hydrogen or e-fuel transport

Fuel and electricity consumption in different powertrains

For the most part, the fuel and electricity consumption values used for the individual powertrain types were based on segment-specific, sales-weighted averages of new car registrations in 2019. For Europe, China, and India, these averages were taken from official test values and then adjusted with real-world factors to represent consumption in real-world driving conditions, including charging losses. In the U.S. analysis, the average fuel and electricity consumption values correspond to the U.S. Environmental Protection Agency's (EPA) five-cycle test, which is found be similar to real-world driving conditions (Tietge et al., 2017).

For PHEVs, the fuel and electricity consumption depends on how much driving occurs in predominantly electric charge-depleting (CD) mode and how much is done in the purely combustion engine charge-sustaining (CS) mode. Note that in CD mode, the electric motor is supported by the combustion engine; in reality, this is better described as a mixed electric and combustion engine mode than a purely electric drive mode. In official test values, the fuel and electricity consumption in the CD and the CS drive modes are weighted, either by an assumed CD mode range-dependent share, as in the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), or by an assumed all-electric range dependent share, as in the New European Driving Cycle (NEDC). Such all-electric range is determined as the part of the CD mode range in which the combustion engine is not running (Riemersma & Mock, 2017). In any case, WLTP and NEDC test values generally assume that on each driving day, PHEVs are started with a fully charged battery and driven in CD mode as long as the battery allows. However, studies have found that average PHEV users charge their cars less frequently than once per driving day. When taken together with the lower electric range and higher fuel consumption in CS mode, the average real-world fuel consumption of individual PHEV models is found to be two to four times higher than indicated by NEDC or WLTP test values (Plötz et al., 2020).

This deviation in PHEV usage is found to vary largely between private and company car users, and between the investigated European countries, the United States, and China. (PHEVs are hardly registered at all in India.) Fuel consumption also varies significantly between individual PHEV models, and user-reported fuel consumption values are only available for a limited number of PHEV models. Therefore, the real-world drive share and fuel consumption values cannot be assessed on a fleet level, and the real-world, drive-share-weighted electricity consumption can only be estimated for individual PHEV models. As such, this study assesses the real-world fuel and electricity consumption values of PHEVs in the respective segments in Europe, the United States, and China with average user-reported data of representative models.

Gasoline, diesel, and natural gas blends

For the gasoline, diesel, and natural gas blends, the GHG emissions per unit of fuel in MJ, L, or kg are based on the current average shares of different fossil and renewable fuel feedstocks and pathways in each region. While these shares are assumed to remain constant in the United States and China, they are considered to change over time in the European Union and India, based on the stated policies of the *Renewable Energy Directive* (RED II) in the European Union and India's *National Policy on Biofuels*.

For each of the considered fuel feedstocks and pathways, GHG emissions corresponding to the production and transport (WTT) as well as to the consumption (TTW) are assessed. For biogenic fuels that are not based on waste and residues, indirect land use change (ILUC) emissions are included. The biogenic carbon credit of biofuels is accounted for in the TTW emissions.

With the projected changes in the fuel blends during the lifetime of the vehicles, the amount of GHG emissions from their consumption also changes. Further, because the annual mileage of passenger cars decreases with vehicle age, the lifetime average carbon intensity of the consumed electricity and hydrogen are adjusted by the decrease in annual mileage. As a result, the fuel blends used in the early years of driving have a higher share of the total GHG emissions than the fuel blends used in later years.

Electricity

The carbon intensity of the electricity consumed by charging BEVs and PHEVs is based on the average life-cycle GHG emissions of the different electric energy sources, their projected mix during the lifetime of the vehicles, and transmission and distribution losses in the electric grid. Note, also, that for renewable energy sources such as wind and solar energy, the life-cycle GHG emissions are considered, in other words, the emissions corresponding to their construction and maintenance. (The energy losses during charging are accounted for in the real-world electricity consumption values.)

Hydrogen

The hydrogen produced today is almost entirely from steam reforming of natural gas, known as “grey hydrogen,” or coal gasification, known as “black hydrogen” (International Energy Agency [IEA], 2019). However, in an increasing number of policy frameworks, including the EU *Renewable Energy Directive* (RED II; European Parliament & Council of the European Union, 2018), the production of hydrogen via renewable energy-based electrolysis, “green hydrogen,” and via natural gas in combination with carbon capture and storage (CCS), “blue hydrogen,” is incentivized. Therefore, these two hydrogen pathways are considered to become increasingly important in the next decades. Due to the large differences between the GHG emissions impact of these four hydrogen pathways, and high uncertainty regarding their future shares of hydrogen used in road transport, this study presents the life-cycle GHG emissions of FCEVs for each hydrogen pathway individually.

For grey hydrogen, the life-cycle GHG emissions include the production and transport of natural gas, including methane leakage, and the formation and compression of hydrogen. For blue hydrogen, a share of the emissions from the steam reforming of natural gas is removed by CCS. The life-cycle GHG emissions of black hydrogen consider the production of coal and its gasification to hydrogen, both including methane emissions, and the emissions corresponding to hydrogen compression. For green hydrogen, the life-cycle GHG emissions of renewable electricity production, as well as the energy losses during the electrolysis and the compression of hydrogen, are considered. While short-distance transport of hydrogen is considered, the energy losses of long-distance transport, in other words for hydrogen produced on a different continent, are not considered.

E-fuels

E-fuels, or electrofuels, are considered to be produced from additional renewable electricity-based hydrogen and CO_2, either from industry exhaust gases or from direct air capture. The life-cycle GHG emissions of their production are based on the life-cycle GHG emissions of the used renewable energy, which includes the emissions from the production of new power plants, and this study further considers the energy losses of electrolysis and fuel production via a methanol or Fischer-Tropsch pathway. As with biofuels, the CO_2 credit of their production is accounted for in the TTW emissions.

2.4 HIGHLIGHT: BATTERY PRODUCTION EMISSIONS

The GHG emissions from producing the batteries used in BEVs and PHEVs are determined with regionally adjusted GHG emission factors, in kg $CO_{2\,eq.}$/kWh, and the respective battery capacities in kWh. For both 2021 and 2030 cars, this study considers a significantly lower carbon intensity for battery production than earlier studies, and the following paragraphs highlight how this difference is rooted in the latest data on battery production, the current state-of-the-art battery chemistry, and regionally adjusted battery production and import shares. Together these result in estimated GHG emissions from producing the batteries for BEVs that are very similar to those from the production of the hydrogen system in FCEVs and which are only about a third of the total production emissions of BEVs.

Section A.3 of the Appendix further discusses and estimates the GHG emissions benefit of second-life usage and battery recycling.

Latest data on battery production

The life-cycle GHG emissions corresponding to the extraction and processing of materials used in lithium-ion batteries and the battery production itself are derived from the latest version of the GREET model (Argonne National Laboratory, 2020). As described by Dai et al. (2019), the GREET model uses primary industry data on the energy consumption of the cathode material and cell production, and considers the GHG emissions of module and pack assembly as negligible. Compared to earlier data on battery production (Romare & Dahllöf, 2017; Hall & Lutsey, 2018), which were mostly based on approximations and secondary data, the GREET data shows lower energy consumption and thus lower GHG emission values. Additionally, in the 2020 version of the GREET model, the specific energies per kg of battery material are updated to higher values, and this further decreases the carbon intensity per kWh of battery capacity.

State-of-the-art battery chemistry

The carbon intensity of battery production varies with the battery chemistry. Today's BEV and PHEV models are mostly equipped with NMC622-graphite and NCA-graphite batteries, as formerly used NMC111-graphite batteries have been phased out of the market (Slowik et al., 2020). Differing also from recent literature (Dai et al., 2019; Kelly et al., 2019; Emilsson & Dahllöf, 2019), this study considers NMC622-graphite instead of NMC111-graphite batteries for 2021 cars.

Regional battery production and import shares

The GREET model can be adjusted to battery production in Europe, the United States, China, South Korea, and Japan (Kelly et al., 2019). Accordingly, this study uses regionally adjusted values for the carbon intensity of the electricity used for the cathode material production and cell manufacturing, and for the supply chain of aluminum and nickel. Table 2.3 shows the carbon intensity of producing batteries with different cathode materials in these regions in 2021.

Table 2.3. GHG emissions of the production of lithium-ion batteries with different cathode chemistries in the major battery producing regions in 2021.

kg $CO_{2\ eq.}$/kWh	Europe	United States	China	South Korea	Japan
NMC111-graphite	56	60	77	69	73
NMC622-graphite	**54**	**57**	**69**	**64**	**68**
NMC811-graphite	53	55	68	63	67
NCA-graphite	57	59	72	67	70
LFP-graphite	34–39	37–42	51–56	46–50	50–55

For batteries used in Europe, the United States, and China, the values in Table 2.3 are weighted by the respective 2019 shares of batteries produced in or imported from Europe, the United States, China, South Korea, and Japan (data from EV-Volumes). For the batteries used in India, the same factor as for China is used. The carbon intensity of the average battery used in new cars in Europe and the United States thus corresponds to 60 kg $CO_{2\ eq.}$/kWh, while 68 kg $CO_{2\ eq.}$/kWh are considered for new cars in China and India.

In Table 2.4, these average carbon intensities are combined with the battery capacities of BEVs and PHEVs in the considered segments in each region. For BEVs in Europe, the United States, and China, the battery capacities correspond to sales-weighted averages of new registrations in 2019 (data from EV-Volumes and China EV100). For BEVs in India and for PHEVs in all applicable regions (i.e., Europe, the United States, and China), battery capacities are taken from representative models (see **Section A.2** of the Appendix).[1]

Table 2.4. Battery capacity and GHG emissions of the production of batteries for BEVs and PHEVs registered in Europe, the United States, China, and India in 2021.

		BEV		PHEV	
		Battery capacity (kWh)	GHG emissions (t $CO_{2\ eq.}$)	Battery capacity (kWh)	GHG emissions (t $CO_{2\ eq.}$)
Europe (60 kg $CO_{2\ eq.}$/kWh)	**Small**	45.0	2.7	—	—
	Lower medium	45.0	2.7	9.7	0.6
	SUV	70.0	4.2	13.8	0.8
United States (60 kg $CO_{2\ eq.}$/kWh)	**Passenger car**	70.0	4.2	17.0	1.0
	SUV	92.0	5.5	12.0	0.7
China (68 kg $CO_{2\ eq.}$/kWh)	**A0**	37.2	2.5	—	—
	A	52.9	3.6	9.1	0.6
	SUV	52.3	3.5	15.8	1.1
India (68 kg $CO_{2\ eq.}$/kWh)	**Hatchback**	23.0	1.6	—	—
	Sedan	23.0	1.6	—	—
	SUV	32.3	2.2	—	—

Lower carbon intensity for batteries produced in 2030

For vehicles expected to be registered in 2030, this study considered NMC811-graphite batteries as the dominant battery chemistry (Slowik et al., 2020). Additionally, with increasing battery manufacturing capacities, the batteries used in 2030 cars in the four regions are assumed to be entirely produced domestically. Further, due to the reduction of the carbon intensity of the power supply, improvements in battery production technologies, and economies of scale, the GHG emissions of producing NMC811-graphite batteries (in kg $CO_{2\ eq.}$/kWh) are assumed to be 20% lower in 2030 than the 2021 values displayed in Table 2.3 (Philippot et al., 2019; Kurland, 2019). At the same time, due to decreased production cost and increased specific energy, the battery capacity in both BEVs and PHEVs is assumed to increase by 20% in 2030. In India, the battery capacity of 2030 BEVs is considered to be twice as high as it is for current models.

2.5 HIGHLIGHT: VEHICLE LIFETIME AVERAGE ELECTRICITY MIX

Given the continuous efforts to decarbonize electricity grids, BEVs are assumed to consume a less carbon intensive electricity mix with each passing year of their lifetime. Any projection of future electricity mix comes with large uncertainty, though, and as a

1 The battery capacity of BEVs in the hatchback, sedan, and SUV segments in India are represented by the Tata Tigor, Mahindra e-Verito, and Tata Nexon. The manufacturer declared capacities of these models (21.5 kWh, 21.2 kWh, and 30.2 kWh) are considered to correspond to the useable capacity. The total battery capacities displayed in Table 2.4 are assumed to be about 7% higher. For the other regions, the BMW 225xe and Mitsubishi Outlander (13.8 kWh variant) represent the lower medium and SUV segments in Europe, the Honda Clarity and Mitsubishi Outlander (12.0 kWh variant) for passenger cars and SUVs in the United States, and Roewe ei6 and BYD Song for the A and SUV segments in China.

result, this study compares a conservative baseline, the Stated Policy Scenario (STEPS) from the IEA's World Energy Outlook (IEA, 2020), with the IEA's more optimistic Sustainable Development Scenario (SDS). The latter projects advancements in the power sector that comport with the Paris Agreement's goal of limiting global warming to "well below" 2 °C.

As discussed in detail in **Section A.2** of the Appendix, the electricity mixes are combined with the Intergovernmental Panel on Climate Change (IPCC)'s global average life-cycle GHG emissions of the different electricity generation technologies (Moomaw et al., 2011) and adjusted by the transmission and distribution losses in the electric grids (IEA, 2021). The results of this for electricity consumption in the European Union (EU 27), the United States, China, and India are displayed in Figure 2.1.

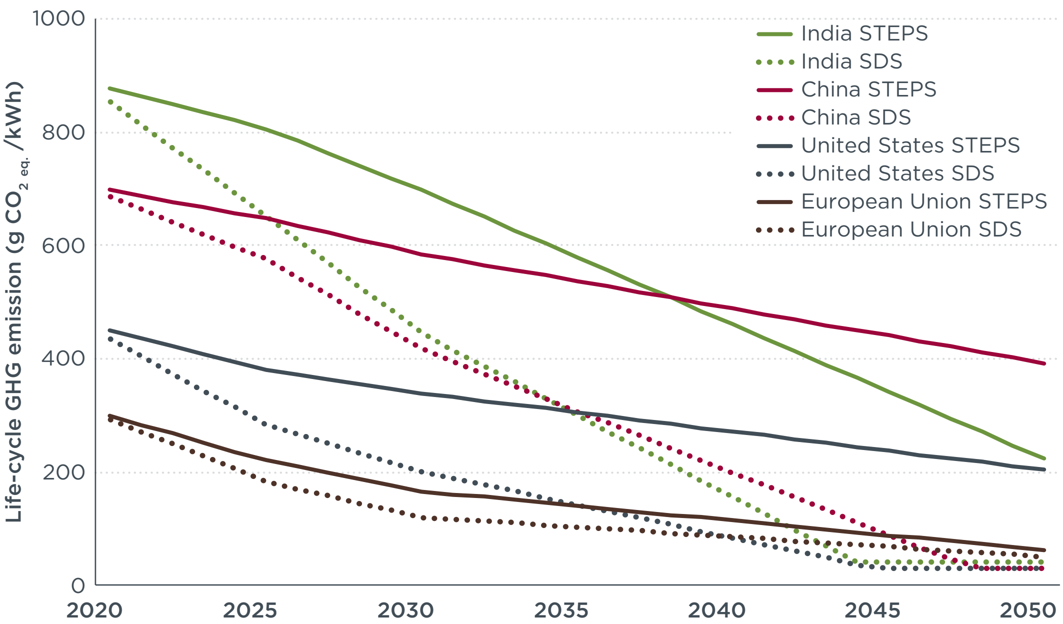

Figure 2.1. Life-cycle GHG emissions of electricity consumption based on an electricity mix of IEA's Stated Policy (STEPS) and Sustainable Development Scenario (SDS), the IPCC's life-cycle GHG emission factors, and energy losses in the grids.

Over the lifetime of cars registered in 2021, the life-cycle carbon intensities in the two IEA scenarios translate into average values of 164–199 g $CO_{2\ eq.}$/kWh for the European Union, 239–357 g $CO_{2\ eq.}$/kWh for the United States, 509–622 g $CO_{2\ eq.}$/kWh for China, and 561–746 g $CO_{2\ eq.}$/kWh for India. For 2030 cars, these values are significantly lower (see **Table A.21** in the Appendix).

Section A.2 of the Appendix also discusses the estimated carbon intensity of the average gasoline, diesel, and natural gas blends in detail, but compared to the improvement of the electricity mix, these changes are much less significant.

2.6 HIGHLIGHT: 20-YEAR GLOBAL WARMING POTENTIAL OF METHANE

This study assesses the life-cycle emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). Usually, these emissions are translated into equivalent of CO_2 ($CO_{2\ eq.}$) based on their 100-year GWP, 1 g CH_4 = 30 g $CO_{2\ eq.}$ for methane and 1 g N_2O = 265 g $CO_{2\ eq.}$ for nitrous oxide (IPCC, 2013). When looking at a 20-year timescale, however, the relative impact of methane compared to CO_2 is three times higher than in the 100-year GWP, 1 g CH_4 = 85 g $CO_{2\ eq.}$. For nitrous oxide, though, the 20-year GWP of 1 g N_2O = 264 g $CO_{2\ eq.}$ is quite close to its 100-year GWP.

To also compare near-term climate effects, the 20-year GWP of the occurring methane emissions is estimated in this study. For this, the study focuses on the main sources of methane emissions, which are the production and transport of natural gas, either for direct use in CNG cars or to produce hydrogen. Also, the 20-year GWP of the methane slip emissions from the vehicles is considered.

Upstream methane emissions

Using a top-down approach, the Environmental Defense Fund (EDF) previously estimated the methane emissions of the entire U.S. gas and oil industry to be about 13 million tons per year (Alvarez et al., 2018). Based on bottom-up data on the share of methane emissions from the production of natural gas and oil, the GREET model assigned these emissions to the natural gas and oil production separately. They amount to 0.26 g CH_4 per MJ of natural gas and only 0.05 g CH_4 per MJ of gasoline (Argonne National Laboratory, 2020). As this is indicated by data on global methane emissions (Hmiel et al., 2020) the methane leakage emissions from natural gas production in the other regions of this study are expected to be similar to the United States. For natural gas, these emissions correspond to a 100-year GWP of 7.8 g $CO_{2\ eq.}$/MJ and a 20-year GWP of 22.1 g $CO_{2\ eq.}$/MJ. Thereby, the 20-year GWP of the EU average natural gas blend, for instance, is 18% higher than the 100-year-GWP, 14.3 g $CO_{2\ eq.}$/MJ. For comparison, the 20-year GWP of the gasoline blend would only be about 3% higher than the 100-year GWP, 2.5 g $CO_{2\ eq.}$/MJ.

Natural gas-based hydrogen

When converting natural gas into hydrogen, the upstream methane leakage emissions amount to 0.34 g CH_4 per MJ hydrogen (Argonne National Laboratory, 2020), and this corresponds to a 100-year GWP of 10.2 g $CO_{2\ eq.}$/MJ and a 20-year GWP of 28.9 g $CO_{2\ eq.}$/MJ. (Details are in the Appendix.) As a result, natural gas-based hydrogen has a 20-GWP that is 16%–18% higher than its 100-year GWP. Note that the upstream methane emissions are the same for blue hydrogen; the difference there is that the CO_2 emissions from the steam-reforming process are offset by CCS.

Methane slip in the vehicles

As discussed in **Section A.2** of the Appendix, the methane slip emissions from CNG cars in Europe amount to only about 0.06 g CH_4/km (Prussi et al., 2020; Valverde & Giechaskiel, 2020; Vojtíšek-Lom et al., 2018; Hagos & Ahlgren, 2018), which corresponds to an additional 100- and 20-year GWP of 2–5 g $CO_{2\ eq.}$/km. For CNG cars in China, although not addressed in this study, several studies report a high methane slip of 2% (Pan et al., 2020), which corresponds to about 1 g CH_4/km and thus additional 30–85 g $CO_{2\ eq.}$/km for the 100- and 20-year GWP. In the absence of data for CNG cars in India, the study generally assumes the same methane slip as for Europe, but also indicates how high they would be if they were the same as for CNG cars in China.

3 EUROPE

In the European Union and the United Kingdom, which are considered to represent Europe in this study, about 15.5 million new cars were registered in 2019 (Díaz et al., 2020). Of these, 63% were gasoline, including hybrid electric vehicles, 32% were diesel, and 1.6% were gas ICEVs, including CNG and LPG cars. Additionally, the region recently experienced a rapid increase in the share of PHEVs, which grew from 1% of new sales in 2019 to 5% in 2020, and also BEVs, which increased from 2% in 2019 to 6% in 2020, as described by Mock et al. (2021). Furthermore, FCEVs are being discussed as a potential powertrain type for passenger cars in Europe. Based on representative vehicle characteristics, these six powertrain types were compared across the region's most popular passenger car segments, namely the small (18% of new registrations in 2019), lower medium (23%), and sport utility vehicle (SUV) segments (37%, Díaz et al., 2020).

3.1 2021 PASSENGER CARS

Data and assumptions

While this section includes a brief summary of the most influential factors in the life-cycle GHG emissions of the Europe part of the analysis, more details are in the Appendix.

For ICEVs and BEVs, the vehicle characteristics, fuel and electricity consumption, and battery capacity correspond to the segment average values of cars registered in the European Union and the United Kingdom in 2019 (Díaz et al., 2020; EV-Volumes). PHEVs are different and are represented by the most popular models, the BMW 225xe and the Mitsubishi Outlander PHEV.[2] Additionally, the FCEVs correspond to the only two models that were registered in significant quantities in Europe in 2019, the Toyota Mirai (lower medium) and Hyundai Nexo (SUV) (Díaz et al., 2020). In the small passenger car segment, no PHEV or FCEV models were available in 2019.

The fuel and electricity consumption corresponds to average real-world usage. For the fuel consumption of ICEVs, the sales-weighted average NEDC fuel consumption values are adjusted with the average deviation of consumer-reported and NEDC values (Dornoff et al., 2020). The real-world fuel consumption of PHEVs, meanwhile, directly refers to average consumer-reported values of the website spritmonitor.de (Fisch und Fischl GmbH, 2021). For BEVs, sales-weighted average WLTP electricity consumption values are adjusted to real-world conditions based on their average deviation from the electricity consumption values determined by the more realistic ADAC Ecotest (Allgemeiner Deutscher Automobil-Club, 2021). The hydrogen consumption of FCEVs directly corresponds to the ADAC Ecotest values.

For the carbon intensity of the average gasoline, diesel, and natural gas blend, biofuel shares of 5vol.% ethanol (E5), 7vol.% biodiesel and hydrogenated vegetable oil (HVO) (B7), and 3.4vol.% biomethane are considered (Huss & Weingerl, 2020). As described in detail in Appendix **Section A.2** (**Tables A.11–A.14**), the analysis considers the current average share of the respective ethanol, biodiesel, HVO, and biomethane feedstocks, as well as how these shares will change until 2030 in order to meet the requirements of the EU's *Renewable Energy Directive* (RED II, European Parliament & Council of the European Union, 2018).

E-fuels are not included in the average fuel blends. It is expected that the production of e-fuels could only start to ramp up in the 2030–2040 period,[3] and due to their high production cost, would require policy support of €2 to €3 per liter diesel equivalent,

2 The BMW 225xe and Mitsubishi Outlander PHEV correspond to 60% of the lower medium PHEV sales and 37% of the SUV PHEV sales in Europe in 2019, respectively (Díaz et al., 2020).

3 According to the German National Platform on the future of Mobility (NPM), the first large-scale e-fuel production plants (100,000 tonnes or 4 PJ of e-fuels per year) may be expected to enter production from around 2028 (Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1 „Klimaschutz im Verkehr", 2020).

also in the 2030–2050 timeframe (Searle & Christensen, 2018). Given that this amount of support is not currently foreseeable, e-fuels are not considered to be available in any relevant amount during the lifetime of cars registered in 2021 and they are not included in the baseline of this study. For cars expected to be registered in 2030, though, Section 3.2 discusses their potential GHG emission impact.

As highlighted in Section 2.5, the carbon intensity of the vehicle lifetime average electricity mix is based on IPCC's life-cycle GHG emission factors (IPCC, 2013) and the projections of the EU average electricity mix according to the IEA's Stated Policy Scenario (STEPS) and the Sustainable Development Scenario (SDS; IEA, 2020).

The analysis considers that cars in Europe are used for 18 years on average until they reach their end of life (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020; Taszka & Domergue, 2019; Mehlhart et al., 2018b).[4] With average annual mileage for small, lower medium, and SUV segment cars of 11,000 km/a, 13,500 km/a, and 15,000 km/a, respectively (Bäumer et al., 2017), the lifetime mileage of small, lower medium, and SUV segment cars is estimated as 198,000 km, 243,000 km, and 270,000 km. Their annual mileage is considered to decrease by 5% per year (Bäumer et al., 2017), and consequently the fuel and electricity mixes in the vehicles' first years have a higher impact than the mixes near the vehicles' end of life.

LCA results and discussion

Figures 3.1 to 3.3 compare the life-cycle GHG emissions in g $CO_{2\ eq.}$/km of Europe's gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs in the small, lower medium, and SUV car segments. For BEVs, cars powered by the average electricity grid and cars powered only by wind and solar energy (renewables) are shown, and for FCEVs, the figures present cars running on hydrogen from wind and solar energy and natural gas-based hydrogen. For the use phase, they include the GHG emissions of producing fuel or electricity (WTT), of the fuel consumption directly in the vehicle (TTW) and the emissions corresponding to maintenance. For the methane emissions, mostly from natural gas production, also the 20-GWP is indicated. The vehicle production emissions correspond to the production of the battery, the hydrogen system, consisting of a hydrogen tank and a fuel cell, and the rest of the vehicle. While the production of the vehicles corresponds to relatively similar emissions for all powertrain types, the life-cycle GHG emissions of the fuel and electricity production and consumption vary significantly.

4 A lower vehicle lifetime used in earlier vehicle LCA studies may refer to the average age of cars that are deregistered in a certain country, e.g., 13 years in Germany in 2005–2009 (Kraftfahrt-Bundesamt, 2011) or 14 years in the United Kingdom in 2012–2013 (Dun et al., 2015). Especially for countries that export large numbers of second-hand cars, such as Germany (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020) and other European countries (Mehlhart et al., 2018a; United Nations Environment Programme, 2020), these cars continue to be used in other countries. Therefore, the numbers of 13–14 years do not cover the full vehicle lifetime.

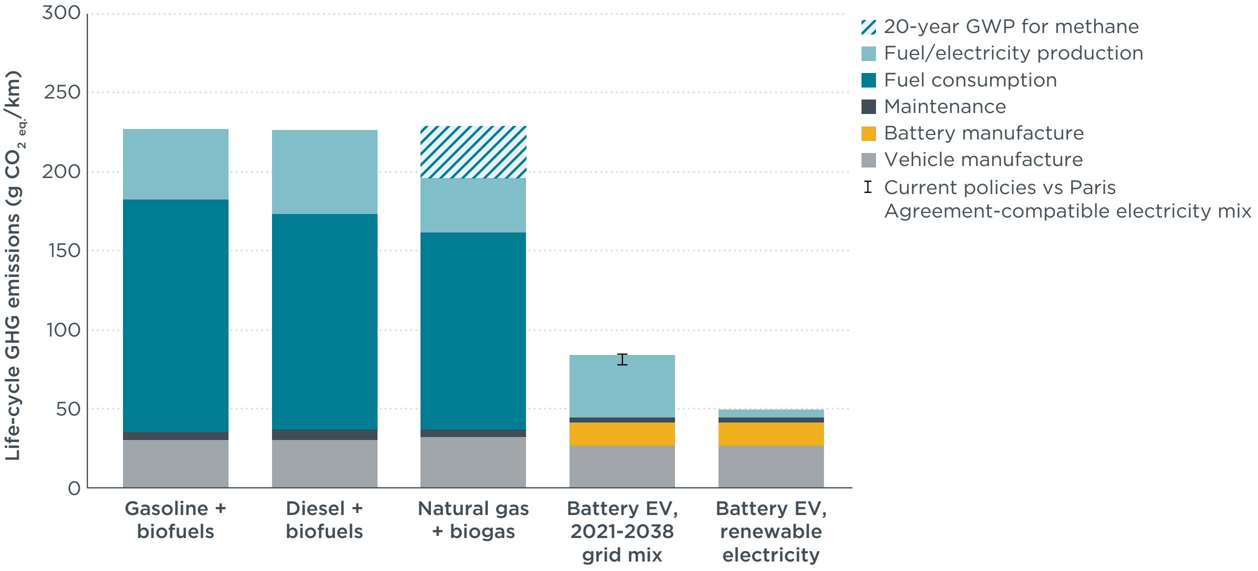

Figure 3.1. Life-cycle GHG emissions of small segment gasoline, diesel, and CNG ICEVs and BEVs registered in Europe in 2021.

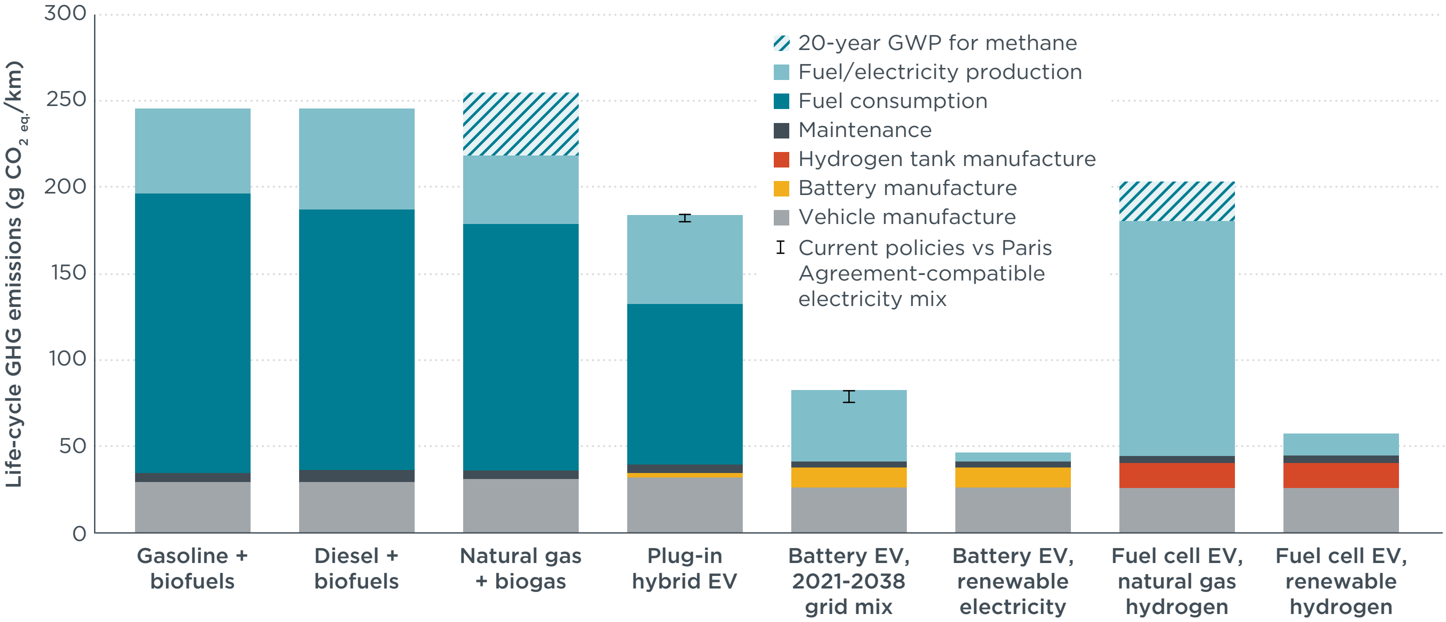

Figure 3.2. Life-cycle GHG emissions of lower medium segment gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs registered in Europe in 2021.

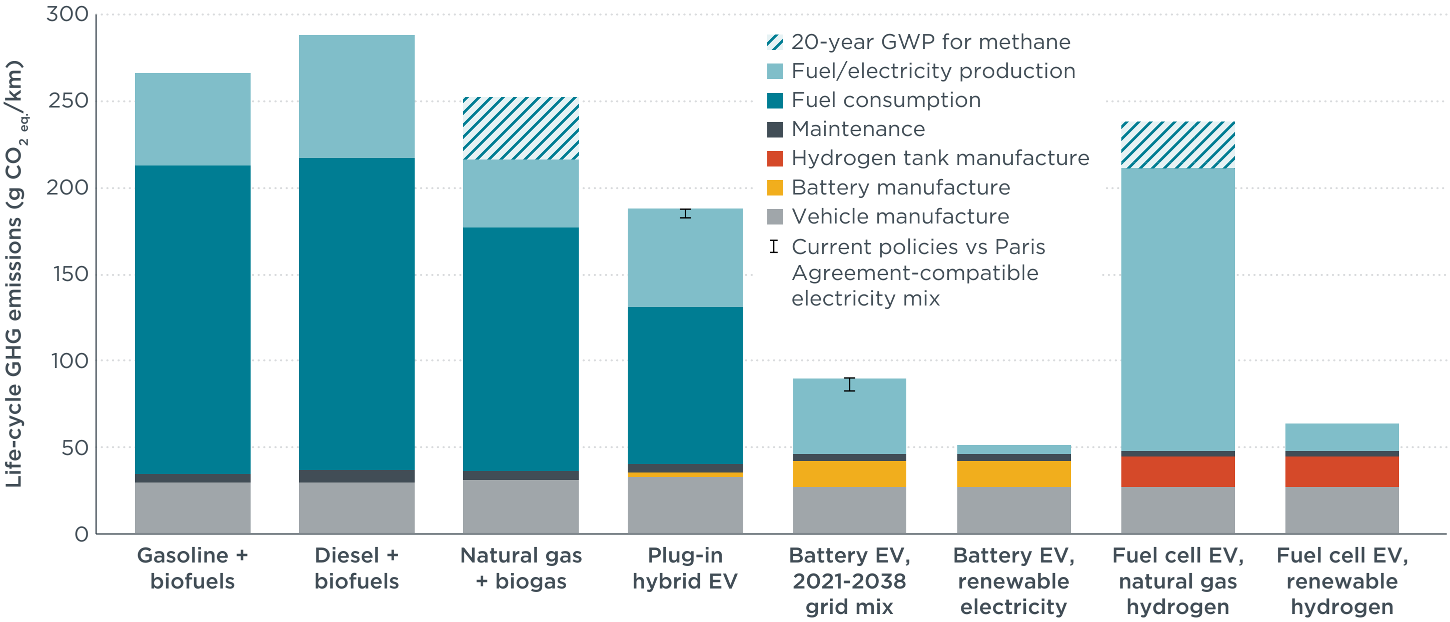

Figure 3.3. Life-cycle GHG emissions of SUV segment gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs registered in Europe in 2021.

Life-cycle GHG emissions of gasoline and diesel cars are twice as high as official tailpipe CO_2 values

The life-cycle GHG emissions of average gasoline- and diesel-powered ICEVs are very similar, and range from 226–227 g $CO_{2\ eq.}$/km for small, 245–246 g $CO_{2\ eq.}$/km for lower medium, and 266–288 g $CO_{2\ eq.}$/km for SUV segment cars. Additionally, compared to the average NEDC test value ranges of 98–111 g CO_2/km for small, 109–122 g CO_2/km for lower medium, and 132–134 g CO_2/km for SUV segment gasoline and diesel cars (Díaz et al., 2020), the life-cycle GHG emissions are more than twice as high. As WLTP values are only estimated to be about 21% higher than NEDC values (Dornoff et al., 2020), WLTP values only account for about half of the life-cycle GHG emissions. The difference between the test values and this study's results stems from the higher fuel consumption in real-world usage, the emissions from fuel production, and the emissions of producing the vehicle.

Biofuels have a small influence on total GHG emissions, and may increase them

The ethanol used in the EU gasoline mix is almost entirely based on corn, wheat, or sugar beet (Huss & Weingerl, 2020). Based on the direct production (Prussi et al., 2020) and ILUC GHG emissions (Valin et al., 2015) of the individual feedstocks presented in **Table A.11**, the current ethanol mix has a life-cycle carbon intensity of 73 g $CO_{2\ eq.}$/MJ, which is 22% lower than the production and combustion emissions of 93 g $CO_{2\ eq.}$/MJ for fossil gasoline (Council of the European Union, 2015). Accordingly, the 5vol.% share of ethanol in the average gasoline blend lowers GHG emissions by only 2%.

For food-based biodiesel feedstocks, of which rapeseed, palm, and soybean oil are the most important in the EU mix, the production emissions, including ILUC, are even higher than the total life-cycle emissions of fossil diesel. With 267 g $CO_{2\ eq.}$/MJ for palm, 208 g $CO_{2\ eq.}$/MJ for soybean, and 116 g $CO_{2\ eq.}$/MJ for rapeseed oil-based biodiesel (Prussi et al., 2020; Valin et al., 2015), they exceed the 95 g $CO_{2\ eq.}$/MJ for fossil diesel by up the three times (Council of the European Union, 2015; **Table A.12**).

Biodiesel produced from used cooking oil, in contrast, corresponds to low life-cycle GHG emissions of 8 g $CO_{2\ eq.}$/MJ. For HVO from these feedstocks, the GHG emissions are similar Prussi et al., 2020; Valin et al., 2015; **Table A.13**). Since the average biodiesel and HVO blends in Europe are mostly based on rapeseed and palm oil (Huss

& Weingerl, 2020), the average life-cycle carbon intensity is at 127 g $CO_{2\ eq.}$/MJ for biodiesel and 150 g $CO_{2\ eq.}$/MJ for HVO; this is 34% and 58% higher, respectively, than fossil diesel. Thereby, the carbon intensity of the 7vol.% biodiesel and HVO containing diesel blend corresponds to 98 g $CO_{2\ eq.}$/MJ, which is 2% higher than fossil diesel. As a high ILUC-risk feedstock, palm oil is considered to not account toward the RED II targets, and thus is assumed to be phased out of the EU biodiesel and HVO blends by 2030. In addition, higher targets for advanced biofuels are foreseen in the RED II (European Parliament & Council of the European Union, 2018). Thereby, the GHG emissions of the average biodiesel and HVO mixes are found to decrease and be at or below the level of fossil diesel by 2030 (**Tables A.12 and A.13**).

HEVs correspond to 20% lower life-cycle GHG emissions than conventional cars

Of new gasoline cars registered in Europe in 2019, 6% were full hybrid electric vehicles or HEVs (Díaz et al., 2020). In the lower medium and SUV segments, these show, on average, about 25% lower real-world fuel consumption than comparable conventional gasoline cars (**Table A.2**). As presented in Figure 3.4, the resulting life-cycle GHG emissions of 193 g $CO_{2\ eq.}$/km for lower medium and 218 g $CO_{2\ eq.}$/km for SUV segment HEVs are 20% lower than for comparable conventional cars.

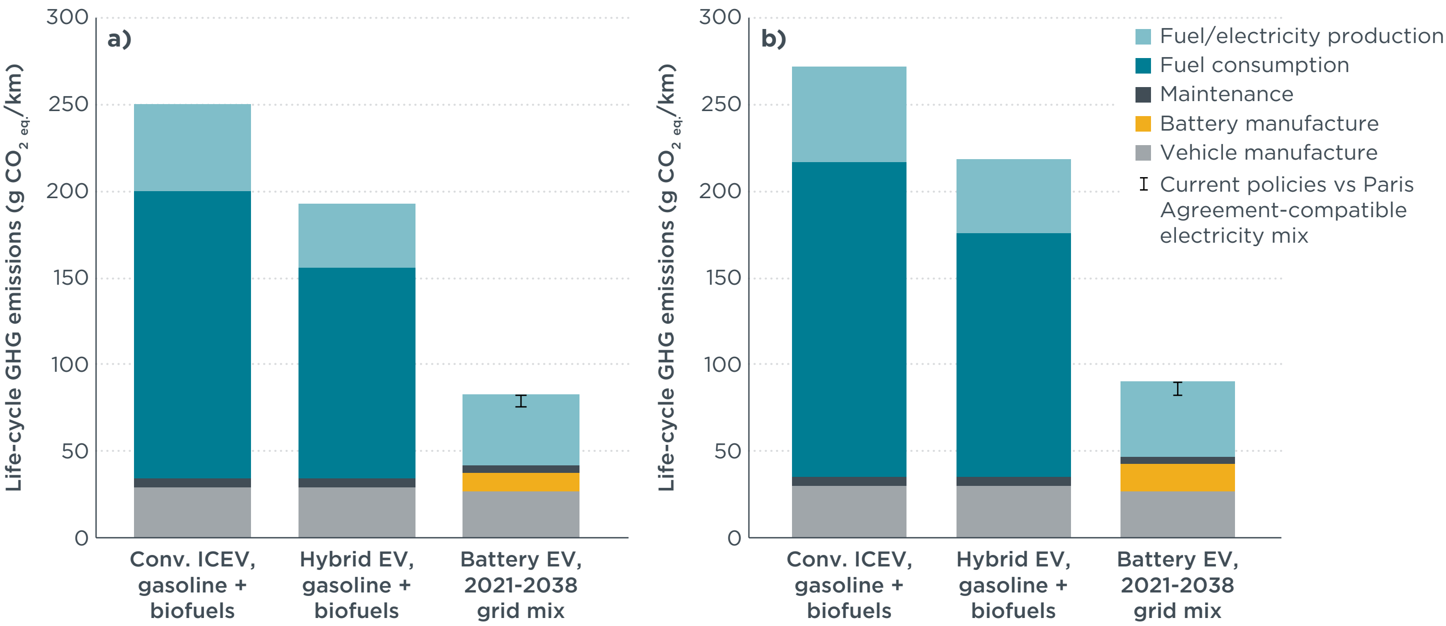

Figure 3.4. Life-cycle GHG emissions of a) lower medium and b) SUV segment conventional gasoline ICEV, gasoline HEV, and average electricity powered BEVs registered in Europe in 2021.

When accounting for near-term climate effects, CNG cars do not offer a GHG emission benefit

CNG cars show 11%–19% lower life-cycle GHG emissions than gasoline cars, at 196 g $CO_{2\ eq.}$/km in the small, 218 g $CO_{2\ eq.}$/km in the lower medium, and 216 g $CO_{2\ eq.}$/km in the SUV segment (Figures 3.1 to 3.3). As discussed in Section 2.6, however, the near-term, 20-year GWP of natural gas-based pathways is significantly higher than their 100-year GWP. Thereby, when considering the 20-year GWP of CNG cars, life-cycle GHG emissions are similar to gasoline and diesel cars, at 228–254 g $CO_{2\ eq.}$/km.

In real-world usage, PHEVs show 25%–31% lower life-cycle GHG emissions than gasoline cars

PHEVs can be driven in a predominantly electric charge-depleting (CD) mode and a purely combustion engine charge-sustaining (CS) mode. As the combustion engine also supports in the CD mode, this drive mode is not purely electric. **Table A.3** in the

Appendix shows that the CD mode fuel consumption varies between PHEV models; for example, it is 2.5 L/100 km for the BMW 225xe and 1.3 L/100 km for the Mitsubishi Outlander (Allgemeiner Deutscher Automobil-Club, 2021). If the considered PHEV models would hypothetically only be driven in the CD mode, thus only drive short distances and start each trip with a charged battery, their life-cycle GHG emissions impact would be 142–148 g $CO_{2\ eq.}$/km for the BMW 225xe and 118–126 g $CO_{2\ eq.}$/km for the Mitsubishi Outlander. Driving the two PHEV models only in the CS mode, in contrast, would correspond to 262 g $CO_{2\ eq.}$/km and 289 g $CO_{2\ eq.}$/km, which would be higher than for the respective average new gasoline cars.

Figures 3.2 and 3.3 depict the life-cycle GHG emissions of driving the PHEVs in the average share of the CD and CS mode, as indicated by the average fuel consumption of private PHEV drivers in Germany. With 4.1 L/100 km for the BMW 225xe and 4.0 L/100 km for the Mitsubishi Outlander (Fisch und Fischl GmbH, 2021), the real-word fuel consumption is about twice as high as the respective NEDC values of 1.9 L/100 km and 1.8 L/100 km. As presented in **Table A.3** in the Appendix, the average real-world fuel consumption values correspond to CD drive shares of 69% and 63%. Weighted by these shares, the CD and CS mode fuel and electricity consumption results in life-cycle GHG emissions are 180–184 g $CO_{2\ eq.}$/km for the BMW 225xe and 182–187 g $CO_{2\ eq.}$/km for the Mitsubishi Outlander. These values correspond to 25%–31% lower emissions than average new gasoline cars in the lower medium and SUV segment.

As estimated by Plötz et al. (2020), private PHEVs in Germany are on average charged on about three out of four driving days, while company car PHEVs are charged less than every second driving day. Both are significantly below the daily charging assumed in NEDC and WLTP test values. Combined with a lower electric range and a higher fuel consumption in the combustion engine mode than in the test values, which are also observed with BEVs and gasoline ICEVs, respectively, the real-world fuel consumption of PHEVs is two to four times as high as indicated by NEDC and WLTP values. With fuel consumption two times higher than indicated by the respective NEDC and WLTP values, the two models selected as representatives in this study are in the lower end of this range.

BEVs have 63%–69% lower life-cycle GHG emissions than gasoline cars

The life-cycle GHG emissions of average BEVs registered in 2021 are estimated to be 77 –84 g $CO_{2\ eq.}$/km for small, 76–83 g $CO_{2\ eq.}$/km for lower medium, and 82–90 g $CO_{2\ eq.}$/km for SUV segment cars, depending on whether the electricity mix is projected to develop according to the IEA's STEPS (upper values) or the SDS (lower values). These values correspond to 63%–69% lower life-cycle GHG emissions than average gasoline cars.

The life-cycle GHG emissions of BEVs vary with the electricity mix in European countries

Figure 3.5 shows the life-cycle GHG emissions of driving an average European new lower medium segment car in the five largest European new car markets. The projections of the respective country-level electricity mixes are based on the central estimate of the Joint Research Center (JRC)'s POTEnCIA model (Mantzos et al., 2019). On an EU plus UK level, this scenario results in a similar carbon intensity as for the European Union (without the United Kingdom) in the IEA's STEPS. Although the life-cycle GHG emissions of driving BEVs in Germany, 104 g $CO_{2\ eq.}$/km, are significantly higher than for driving them in the United Kingdom, 67 g $CO_{2\ eq.}$/km, France, 49 g $CO_{2\ eq.}$/km, Italy, 69 g $CO_{2\ eq.}$/km, or Spain, 64 g $CO_{2\ eq.}$/km, the GHG emissions are 60%–80% lower than average European new gasoline cars in all four countries.

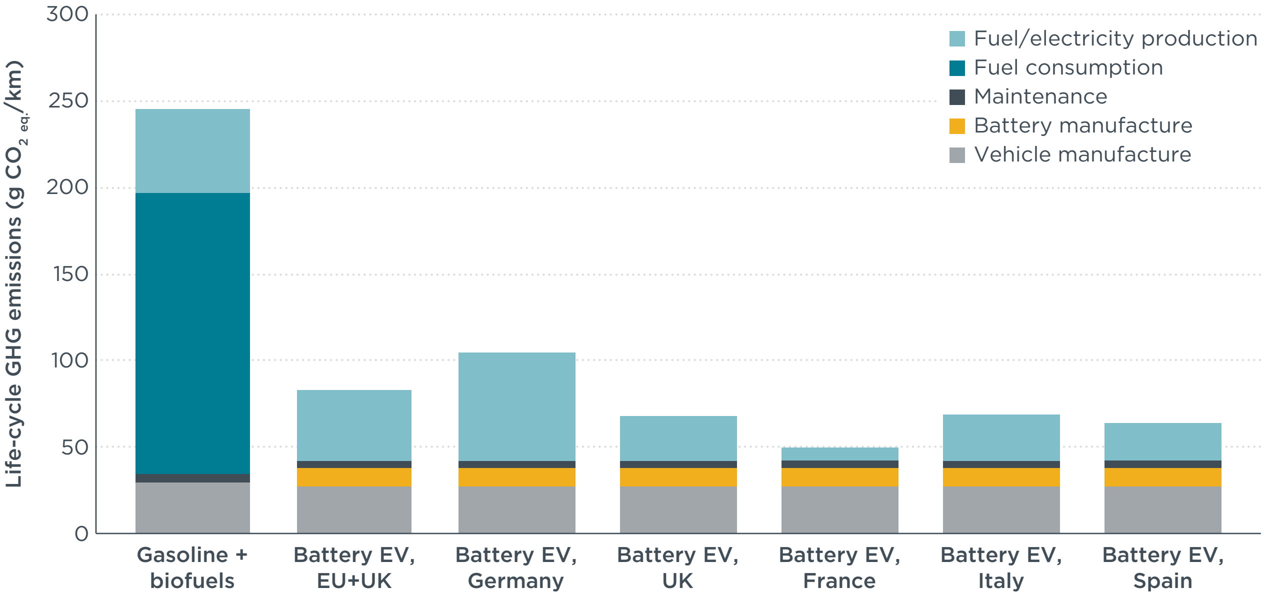

Figure 3.5. Life-cycle GHG emissions of lower medium segment BEVs registered in Europe in 2021, with the vehicle lifetime average electricity mix in the European Union and United Kingdom, Germany, United Kingdom, France, Italy and Spain, compared to gasoline ICEVs.

Renewables-powered BEVs and FCEVs show 76%–81% lower emissions than gasoline cars

When solely using electricity from renewable energy, the life-cycle GHG emissions of BEVs in all three passenger car segments are in the range of 47–51 g $CO_{2\ eq.}$/km. Similarly, FCEVs powered by renewable electricity-based hydrogen correspond to 58 g $CO_{2\ eq.}$/km for the lower medium and 64 g $CO_{2\ eq.}$/km for the SUV segment. These levels are 76%–81% lower than average gasoline cars.

Driving on electricity-based hydrogen requires three times more energy than BEVs

Producing hydrogen by electrolysis currently corresponds to an energy efficiency of 65% (Prussi et al., 2020) and that is expected to increase to 70% in 2030 and 80% in 2050 (Heinemann et al., 2019). Therefore, this study considers an average value of 70%, which corresponds to an energy loss of 0.43 MJ per MJ hydrogen during electrolysis. Adding another 0.25 MJ per MJ hydrogen during compression (Prussi et al., 2020) results in an energy demand of 1.68 MJ per MJ hydrogen. With a hydrogen consumption of 1.0 kg (120 MJ) hydrogen per 100 km, this amounts to an energy demand of 201 MJ per 100 km. This value is almost three times (272%) as high as the energy consumption of average lower medium BEVs of 20.6 kWh (74.2 MJ) per 100 km, including charging losses.

Thereby, as depicted in Figure 3.6, using EU grid electricity instead of solely renewables for the hydrogen production would correspond to 137–156 g $CO_{2\ eq.}$/km, depending on whether the STEPS or the SDS electricity mix projections are considered. These levels are twice as high as for comparable BEVs.

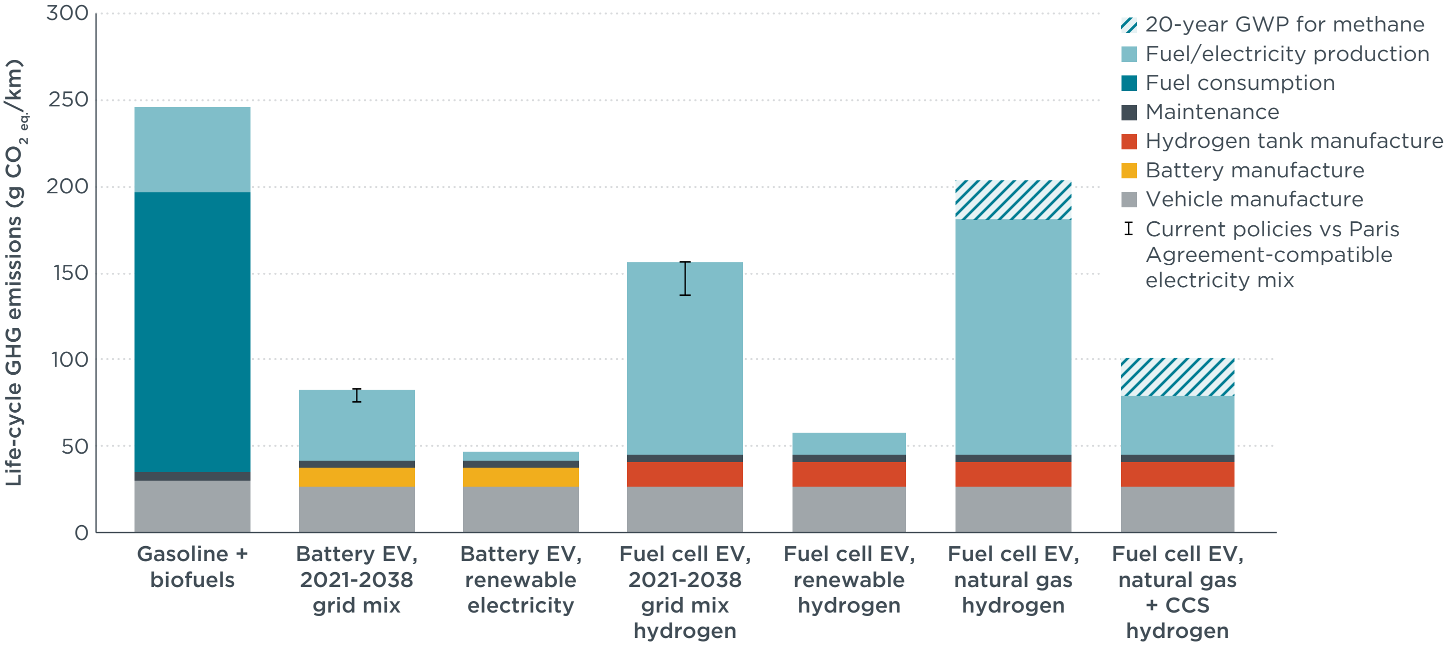

Figure 3.6. Life-cycle GHG emissions of 2021 lower medium car segment BEVs and FCEVs using the EU average electricity mix or only renewable electricity and FCEVs using natural gas derived hydrogen with and without CCS, compared to gasoline ICEVs.

FCEVs powered by natural gas-based hydrogen have similar GHG emissions as CNG cars

As presented in Figures 3.2 and 3.3, the life-cycle GHG emissions of lower medium and SUV segment FCEVs amount to 181 g $CO_{2\ eq.}$/km and 211 g $CO_{2\ eq.}$/km, when powered by natural-gas based grey hydrogen. These emissions are similar to CNG cars, which directly use natural gas for combustion in the car and correspond to 21%–26% lower emissions than gasoline cars. Same as for CNG cars, the upstream methane emissions for FCEVs powered by grey hydrogen result in significantly higher GHG emissions when considering the 20-year GWP. With 203 g $CO_{2\ eq.}$/km for lower medium and 238 g $CO_{2\ eq.}$/km for SUV segment FCEVs, they are only 11%–17% lower than for gasoline cars.

CCS reduces the GHG emissions of natural gas-based hydrogen

When some of the CO_2 emissions from steam-reforming of natural gas to produce hydrogen are offset by CCS, the life-cycle GHG emissions can be significantly reduced (**Table A.22**). For lower medium segment FCEVs, they are at 79 g $CO_{2\ eq.}$/km for the 100-year GWP. As presented in Figure 3.6, this level is 68% lower than for average gasoline cars. When considering the 20-year GWP, the GHG emissions amount to 101 g $CO_{2\ eq.}$/km, which is 59% lower than for gasoline cars.

3.2 2030 PASSENGER CARS

Data and assumptions

In the stated policy framework of the current version of the 2030 CO_2 standards for passenger cars, the average WLTP CO_2 emission levels of new passenger cars in the European Union (plus Iceland, Liechtenstein, and Norway) have to be reduced by 37.5% compared to 2021 (European Parliament & Council of the European Union, 2019). In order to incentivize manufacturers to increase the BEV, PHEV, and FCEV shares in their fleets, the regulation sets a zero- and low-emission vehicle (ZLEV) sales target of 35% for 2030 and rewards manufacturers that outperform this target by up to 5% by relaxing the overall CO_2 threshold by up to 5% (Mock, 2019). While BEVs are counted as full vehicles toward this target, PHEVs are partially counted with a factor of 0.3–1, depending on their official CO_2 values. When considering PHEVs with a factor 0.5, manufacturers could reach a 35% plus 5% ZLEV sales value without PHEVs and a BEV share of 40%, without BEVs and a PHEV share of 80%, or for instance with a BEV and PHEV share of about 27% each. It is assumed that manufacturers will aim to fully exploit these ZLEV benchmark targets (Buysse et al., 2021). With the corresponding shares of BEVs and PHEVs, as well as with the relaxation of the fleet-wide CO_2 target, the average WLTP CO_2 emission levels of the remaining ICEVs would not need to be reduced compared to 2021 vehicles (Mock & Díaz, 2021). Therefore, the real-world fuel consumption of average new gasoline, diesel, and CNG cars in 2030 is considered with the same values as for 2021 cars. With the current review of CO_2 standards, the CO_2 emission target of average new passenger cars registered in 2030 could be decreased to a level at which also the fuel consumption of average new combustion engine vehicles would need to improve (compare Mock & Díaz, 2021; Buysse et al., 2021).

At the same time, due to decreasing costs of battery production, the average battery capacity in 2030 BEVs and PHEVs is considered to be 20% higher than considered for 2021 cars. Nevertheless, due to a shift to NMC811-graphite batteries, improvements in battery production, and the assumed domestic production of the batteries, the total GHG emissions of battery production decrease (see Section 2.4). In the absence of any stated policies that reduce the electricity and hydrogen consumption of BEVs and FCEVs, these are considered to remain at current levels. For PHEVs, the fuel and electricity consumption in CD and CS mode is assumed to be constant. The higher battery capacity, however, is assumed to result in a higher CD mode drive share.

As discussed in more detail in the Appendix (see also **Tables A.11–13**), the average mix of biofuels in the average gasoline and diesel blend correspond to the requirements of the *Renewable Energy Directive* for 2030 (RED II; European Parliament & Council of the European Union, 2018). E-fuels are not considered in the baseline of this study. The policy support needed to price e-fuels competitively is currently not foreseeable, and therefore the potential GHG emissions impact of e-fuels is discussed only in a sensitivity analysis. The average electricity mix used for PHEVs and BEVs is based on the average 2030–2047 electricity mix in the IEA's STEPS and SDS projections.

LCA results and discussion

According to the considerations stated above, it is assumed that manufacturers will reach the 2030 CO_2 emission targets by fully exploiting the ZLEV sales targets rather than by improving the fuel efficiency of average combustion engine vehicles. Under this scenario, results presented in Figures 3.7 to 3.9 show the life-cycle GHG emissions of average gasoline, diesel and CNG cars expected to be registered in 2030 are only about 2% lower than for today's cars.

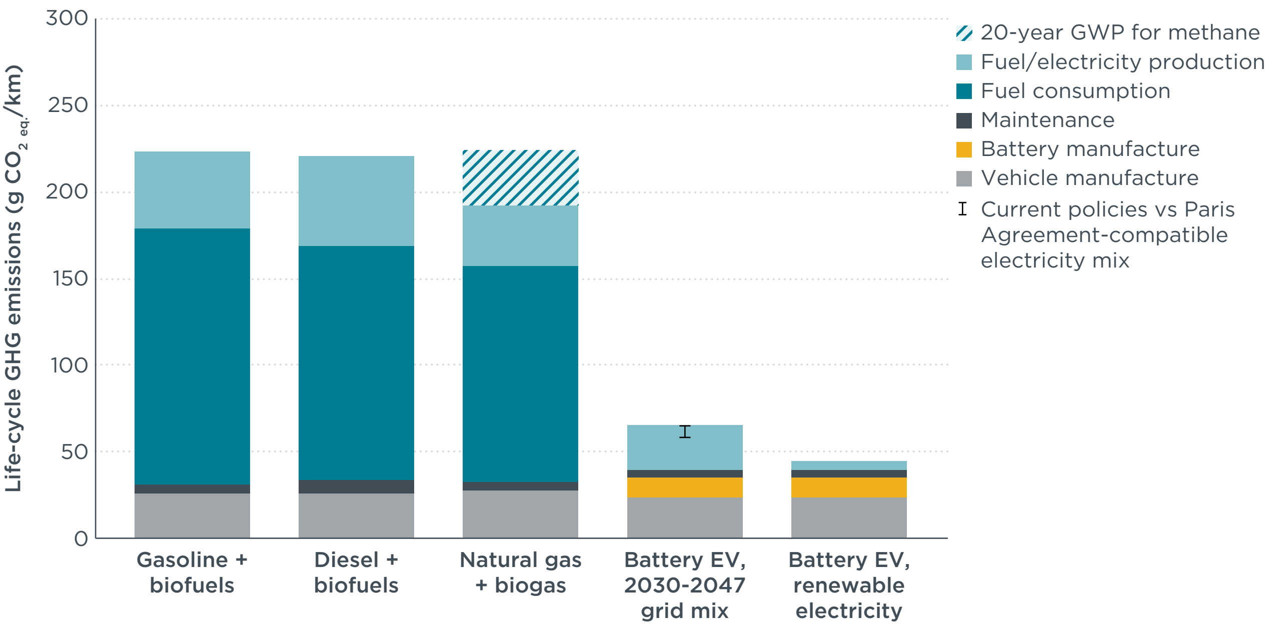

Figure 3.7. Life-cycle GHG emissions of lower medium segment gasoline, diesel, and CNG ICEVs, and BEVs projected to be registered in Europe in 2030.

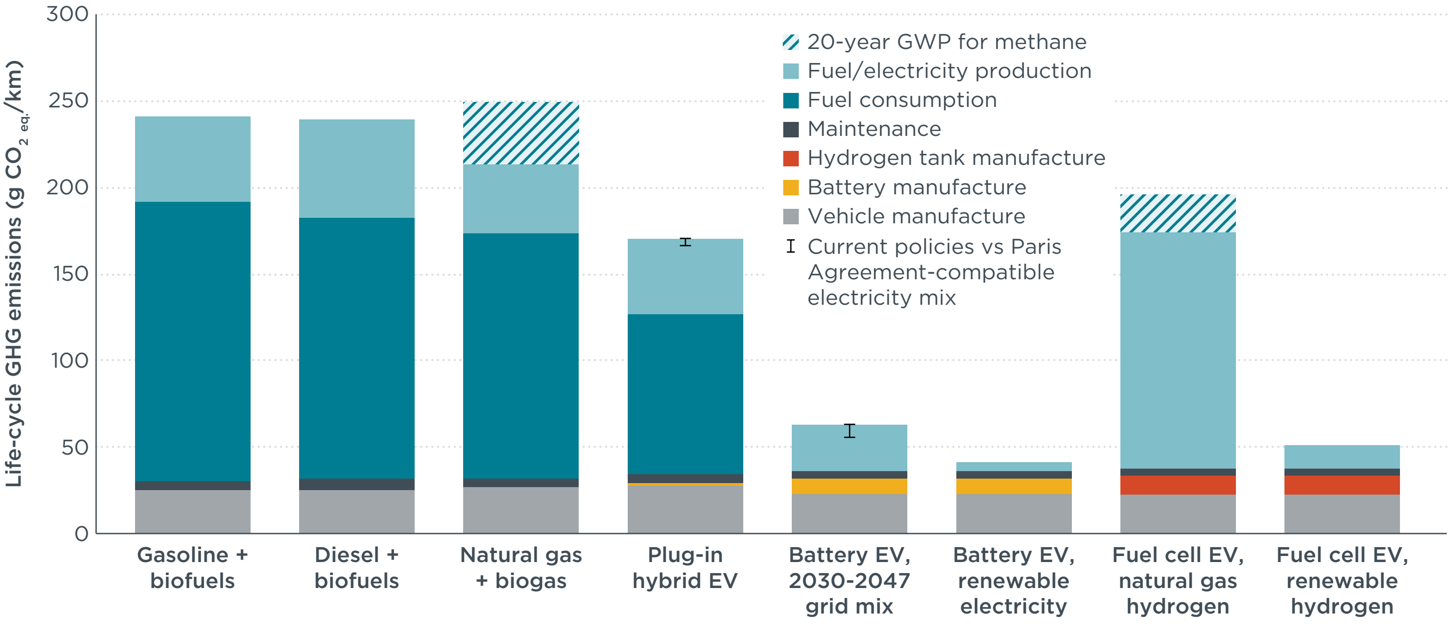

Figure 3.8. Life-cycle GHG emissions of lower medium segment gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in Europe in 2030.

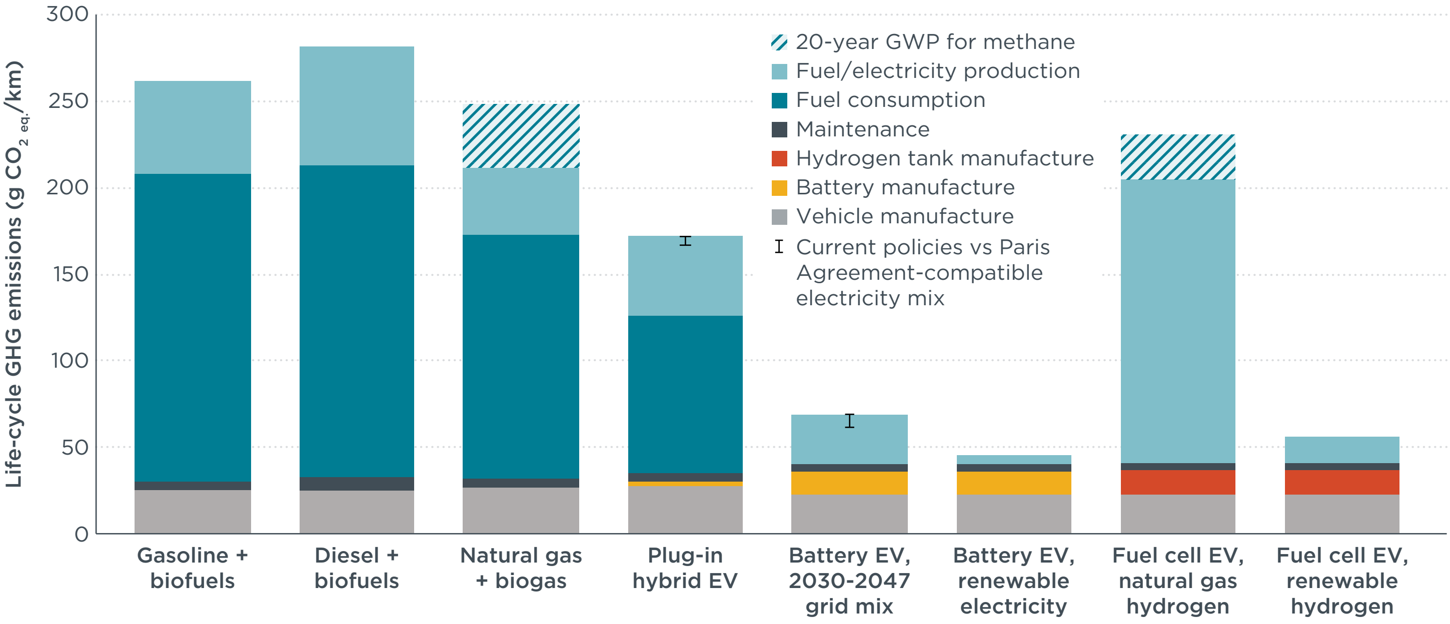

Figure 3.9. Life-cycle GHG emissions of SUV segment gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in Europe in 2030.

While small, lower medium, and SUV segment gasoline and diesel cars show emissions of 220–222 g $CO_{2\ eq.}$/km, 239–241 g $CO_{2\ eq.}$/km and 261–281 g $CO_{2\ eq.}$/km, respectively, CNG cars in these segments correspond to 191 g $CO_{2\ eq.}$/km, 213 g $CO_{2\ eq.}$/km and 211 g $CO_{2\ eq.}$/km. The 20-year GWP of CNG cars in the three segments is similar to gasoline and diesel cars, at 224 $CO_{2\ eq.}$/km, 250 $CO_{2\ eq.}$/km, and 247 $CO_{2\ eq.}$/km.

2030 PHEVs are expected to correspond 34%–40% lower emissions than gasoline cars

With a 20% higher battery capacity and thus longer range, the electric drive share of the two PHEV models considered, one in the lower medium and one in the SUV segment, is estimated to increase by about 5%.[5] For both models, this would reduce the fuel consumption by 10% and increase the electricity consumption by the same amount. Depending on whether the STEPS or the SDS projections of the electricity mix are considered, the life-cycle GHG emissions of hypothetical 2030 variants of the BMW 225xe and Mitsubishi Outlander correspond to 156–160 g $CO_{2\,eq.}$/km and 157–162 g $CO_{2\,eq.}$/km. These numbers correspond to 34%–40% lower GHG emissions than the respective segment average gasoline cars. Without increasing the battery capacity and thereby the electric drive share, the GHG emissions would be 6% higher, at 166–170 g $CO_{2\,eq.}$/km for the BMW 225xe and 167–172 g $CO_{2\,eq.}$/km for the Mitsubishi Outlander.

2030 BEVs correspond to 71%–77% lower GHG emissions than gasoline cars

Even though the study considers a 20% larger battery in 2030, the life-cycle GHG emissions of 2030 BEVs are 23%–26% lower than for 2021 BEVs. Depending on whether the STEPS or the SDS projections on the electricity mix are considered, their life-cycle GHG emissions correspond to 58–65 g $CO_{2\,eq.}$/km for small, 56–63 g $CO_{2\,eq.}$/km for lower medium, and 61–68 g $CO_{2\,eq.}$/km for SUV segment cars. Thereby, segment average BEVs registered in 2030 correspond to 71%–77% lower life-cycle GHG emissions than average gasoline cars in 2030.

All three hydrogen pathways remain at similar emission levels as for 2021 cars

The life-cycle GHG emissions of 2030 FCEVs driving on hydrogen are 6–8 g $CO_{2\,eq.}$/km lower, due to reduced emissions of the vehicle and hydrogen system manufacture, and otherwise remain at the same levels as for cars registered in 2021.

Driving solely on e-fuels would require six times more electricity than using BEVs

An average new lower medium diesel car consumes 6.0 L of diesel (B7) per 100 km. As presented in Figure 3.10, this corresponds to an energy consumption of 2.1 MJ per km. When optimistically assuming that the production of synthetic diesel from renewable electricity, either via electrolysis, reversed water-shift reaction, and Fischer-Tropsch synthesis or via electrolysis and methanol synthesis, it corresponds to an energy efficiency of 50% (Heinemann et al., 2019; Prussi et al., 2020) and the production of this amount of e-fuels would require 4.2 MJ electricity. This is about 6 times the energy consumption of 20.6 kWh per 100 km for an average lower medium BEV and two times as high as for driving on electricity-based hydrogen.

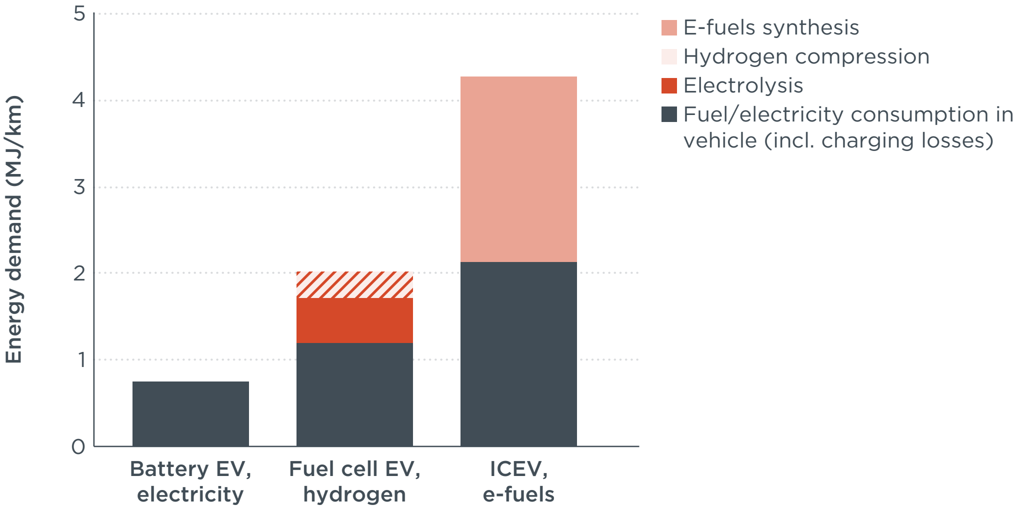

Figure 3.10. Energy demand of medium-size BEVs, FCEVs powered by electricity-based hydrogen, and ICEVs powered by e-fuels.

5 A 20% higher battery capacity is assumed to increase the NEDC all-electric range of the BMW 225xe from 57 km to 68 km, while the range of the Mitsubishi Outlander would increase from 54 km to 65 km. With the correlation between NEDC range and real-world electric drive share in Plötz et al. (2020) it is estimated that for both models, the electric drive share would increase by about 5%.

Due to low expected production volumes, the impact of e-fuels is limited, even after 2030

Because of this high energy demand, the production of e-fuels costs about €3 per liter diesel equivalent more than fossil fuels. If this cost gap were to be bridged with policy support, e-fuels are estimated to be producible in volumes of up to 1 billion liters of diesel equivalent in 2030, 5 billion liters of diesel equivalent in 2040, and 12 billion liters of diesel equivalent in 2050 (Searle & Christensen, 2018). These volumes would not even suffice for aviation, which is more difficult to decarbonize by electrification than road transport. If used in road transport, these volumes correspond to only about 0.3%, 1.7%, and 4.0% of the 300 billion liters of diesel equivalent currently consumed annually in road transport in the European Union. These shares would reduce the lifetime average carbon intensity of the fuel blend consumed by average cars expected to be registered in 2030 by less than 2%. Thus, even when assuming strong policy support for e-fuel production and that e-fuels would only be used in road transport, the producible amounts of e-fuels would not allow for significant reduction of the life-cycle GHG emissions of gasoline or diesel cars.

3.3 SUMMARY AND CONCLUSIONS

In Europe, only BEVs and FCEVs offer a deep reduction in the life-cycle GHG emissions of passenger cars, for both 2021 and 2030. While BEVs offer a large GHG emissions benefit even when powered by average grid electricity, FCEVs require relatively large amounts of renewable energy or to rely on CCS to be a low-carbon powertrain type. All of the other powertrain types investigated offer no reduction, or only minor reductions, in the expected life-cycle GHG emissions compared to today's gasoline or diesel cars. Limited volumes of low-carbon biofuels and e-fuels contribute to these results.

BEVs

Throughout their useful lives, average BEVs registered in 2021 show 63%–69% lower life-cycle emissions than average gasoline cars. When considering a continuously decreasing carbon intensity of the electricity mix in the coming years, the GHG emissions benefit grows for future cars. Thereby, BEVs expected to be registered in 2030 have 71%–77% lower GHG emissions than gasoline cars. BEVs that run entirely on renewables have 78%–81% lower life-cycle GHG emissions than their counterpart gasoline cars.

FCEVs

The life-cycle carbon intensity of FCEVs varies largely according to the hydrogen pathway used. For natural gas-based grey hydrogen, the GHG emissions are 21%–26% lower than the emissions of gasoline cars. When combining this pathway with CCS for blue hydrogen, the GHG emissions are 68% lower than for gasoline cars. Due to potential CO_2 leakage from storage sites, however, CCS requires careful regulation and monitoring (Zhou, 2020).

FCEVs driving on hydrogen solely produced from renewable electricity correspond to 76%–79% lower life-cycle GHG emissions than gasoline cars. To not divert the renewable electricity from an existing use, though, it is important that the renewable energy used is delivered by new, additional power plants. Further, compared to use of this electricity in BEVs, the energy demand of driving FCEVs on electricity-based hydrogen is about three times higher. While renewable generation capacity remains limited, the availability of renewable electricity for this less efficient technology is a concern (Ueckerdt et al., 2021).

PHEVs

For the average real-world usage behavior of the most popular models in the lower medium and SUV segments in 2019, PHEVs correspond to only 25%–31% lower life-cycle GHG emissions than equivalent gasoline cars. Even with an increased electric range and lower carbon intensity of electricity, the life-cycle GHG emissions of PHEVs expected to be registered in 2030 are estimated to correspond to only 34%–40% lower values than for gasoline cars. Compared to 2021 and 2030 BEVs, the life-cycle GHG emissions of PHEVs registered in these years are two to three times higher.

HEVs

The real-world fuel consumption of average HEVs in Europe is about 25% lower than for conventional gasoline cars, and total life-cycle GHG emissions are 20% lower. Compared to average BEVs registered in 2021, the life-cycle GHG emissions of HEVs are about 2.5 times higher.

CNG cars

Across the three major car segments, CNG cars driving on the EU average blend of natural gas and biomethane are found to correspond to 11%–19% lower life-cycle GHG emissions than gasoline cars. Moreover, due to the upstream methane emissions of natural gas, the 20-year GWP of CNG is significantly higher than the 100-year GWP. Considering that near-term GWP, CNG cars registered in 2021 and in 2030 show the same GHG emission levels as gasoline cars.

Biofuels

The European biofuel blend is largely based on food-based biofuel feedstocks and therefore does not significantly improve the life-cycle GHG emissions of the average gasoline and diesel blend. For the current average diesel blend, the life-cycle GHG emissions are even 2% higher than for fossil diesel. With the phase out of palm oil and increased shares of waste-based diesel by 2030, the GHG emissions will still be similar to the fossil fuel. For the EU average gasoline blend, the share of mostly food-based ethanol reduces the life-cycle GHG emissions by 2% compared to fossil gasoline.

More significant reductions of GHG emissions could be achieved through advanced, waste- and residues-based feedstocks. As found in earlier studies (Searle & Malins, 2015; Pavlenko et al., 2019; Pavlenko & Searle, 2020), there is considerable scope to increase the supply of these fuels, but they are eventually limited by feedstock availability. In the mid- to long-term, the use of limited volumes of low-carbon biofuels in other sectors of transportation like aviation (Pavlenko, 2021; O'Malley et al., 2021) and shipping (Zhou et al., 2020) will further reduce the volumes available for passenger cars.

E-fuels

Driving diesel cars on e-fuels corresponds to a six times higher energy demand than when using the electricity in BEVs. Thereby, using e-fuels in passenger cars requires even more renewable energy than using green hydrogen (Ueckerdt et al., 2021). Furthermore, due to the high energy consumption of their production, e-fuels are expected to require strong policy support of €3 per liter diesel equivalent (Searle & Christensen, 2018). As this policy support is currently not foreseeable, e-fuels are not considered in the baseline of this study. As exemplified above, however, even with strong policy support, the producible volume of e-fuels would not affect the GHG emissions of the gasoline and diesel fuel blends consumed over the lifetime of 2021 cars; for 2030 cars, they would reduce the lifetime average carbon intensity of the fuel blends by only 2%. Additionally, the use of e-fuels in sectors of transport which are more difficult to decarbonize than passenger cars, especially in aviation (Pavlenko, 2021; O'Malley et al., 2021), would further limit the volumes available for cars.

4 UNITED STATES

In the United States, about 16 million new light-duty vehicles were registered in 2019. These consisted of SUVs, 48.2%[6], passenger cars, 32.7%, pickup trucks, 15.6%, and vans/minivans, 3.4% (EPA, 2021). In 2019, the vast majority of these vehicles were gasoline ICEVs (98% in 2019, including 4% HEVs), and the shares of new diesel, 0.1%, and CNG cars, 0.0%, were negligible (EPA, 2021). In contrast, the share of BEVs increased from 1.4% in 2019 to 1.9% in 2020, and the share PHEVs was at 0.5% in both 2019 and 2020 (data from EV-Volumes). Despite FCEVs being 0.0% of new car sales in 2019 and 2020, they are discussed as a potential low-carbon alternative in the United States and are thus considered in this study.

4.1 2021 PASSENGER CARS

Data and assumptions

This section provides a summary of the most influential factors in the U.S. part of the analysis. More details are in the Appendix.

Real-world fuel and electricity consumption values, including charging losses, are based on the EPA's five-cycle test, which is reflective of consumer-reported fuel consumption values (Tietge et al., 2017). The segment average fuel consumption of gasoline vehicles is taken from the EPA's Automotive Trends Report (EPA, 2021). For BEVs, the EPA electricity consumption (EPA & U.S. Department of Energy, 2020) and battery capacity of BEVs correspond to the segment-specific averages of cars registered in 2019 (data from EV-Volumes). The EPA hydrogen consumption of the Toyota Mirai and the Hyundai Nexo are used for FCEVs in the passenger car and SUV segments, respectively, because these two models correspond to almost all FCEV sales in 2019.

The real-world average fuel and electricity consumption of passenger car and SUV segment PHEVs correspond to the Honda Clarity and the Mitsubishi Outlander. For these models, the EPA consumption values for driving either on fuel or only on electricity[7] (EPA & U.S. Department of Energy, 2020) are found to represent the 2019 sales-weighted average values in the two segments (data from EV-Volumes). The average real-world share of driving on fuel and electricity are determined from the average user-reported fuel consumption values for the two models on the EPA's MyMPG website (EPA & U.S. Department of Energy, 2021).

The U.S. gasoline blend is considered with an ethanol share of 10vol.%, which is entirely based on corn. Despite higher ambitions in the 2007 *Renewable Fuels Standard* , the realized volumes of cellulosic and advanced biofuels remain at a low level (U.S. Department of Energy, 2021).

Therefore, the corn-based U.S. gasoline blend is also considered to remain constant in future. The life-cycle carbon intensity of the vehicle lifetime average electricity mix is based on the IPCC's life-cycle GHG emission factors (Moomaw et al., 2011) and the projected electricity mixes of the IEA's Stated Policy Scenario (STEPS) and the Sustainable Development Scenario (SDS; IEA, 2020).

The average lifetime of passenger cars and SUVs registered in both 2021 and 2030 is considered to be 18 years, higher than the 15-year lifetime found for cars registered around 1990 (Lu, 2006; more details in the Appendix). With the distribution of the annual mileage per vehicle age in the 2017 National Household Travel Survey (U.S. Department of Transportation, 2017), an average vehicle lifetime of 18 years corresponds to 314,000 km for passenger cars and 337,000 km for SUVs. For both segments, the

6 Including SUVs from the regulatory classes of cars and trucks.

7 The EPA Fuel Economy Guide provides fuel and electricity consumption values for a combustion engine and a purely electric mode, respectively. Differing from the values by the ADAC Ecotest, for instance, the electric mode does not consider the support of the combustion engine consumption.

annual mileage decreases linearly with about 500 km/a each year (U.S. Department of Transportation, 2017). Accordingly, the fuel and electricity mix in the first years has a higher impact on the total GHGs than the mixes close to the vehicles' end of life.

LCA results and discussion

Figures 4.1 and 4.2 present the life-cycle GHG emissions in g $CO_{2\ eq.}$/km of new gasoline ICEVs, PHEVs, BEVs, and FCEVs in the passenger car and SUV segment. They mostly correspond to the production of the fuel or electricity (WTT) and the emissions of fuel consumption directly in the vehicle (TTW) during the vehicle use phase. For the methane emissions, mostly of natural gas production, also the near-term, 20-year GWP is indicated. The figures further include the GHG emissions of the production of the battery, the hydrogen system, and the rest of the vehicles and of maintenance.

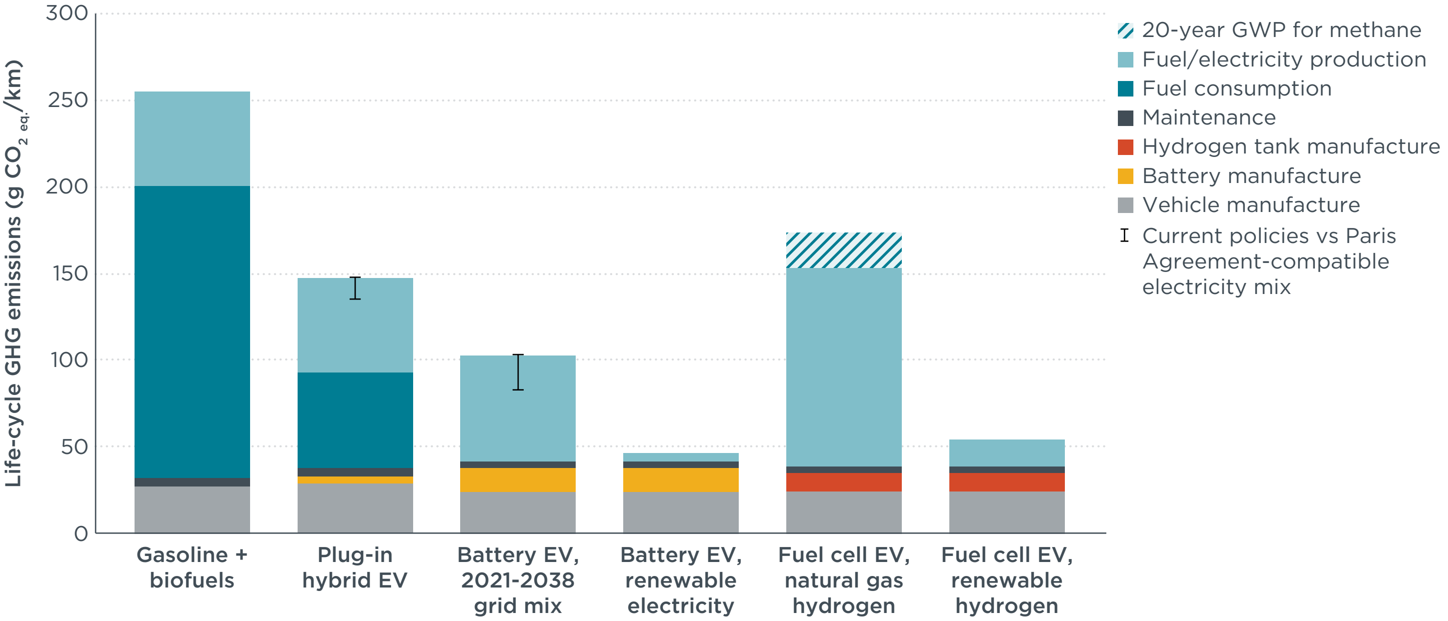

Figure 4.1. Life-cycle GHG emissions of passenger car segment gasoline ICEVs, PHEVs, BEVs, and FCEVs registered in the United States in 2021.

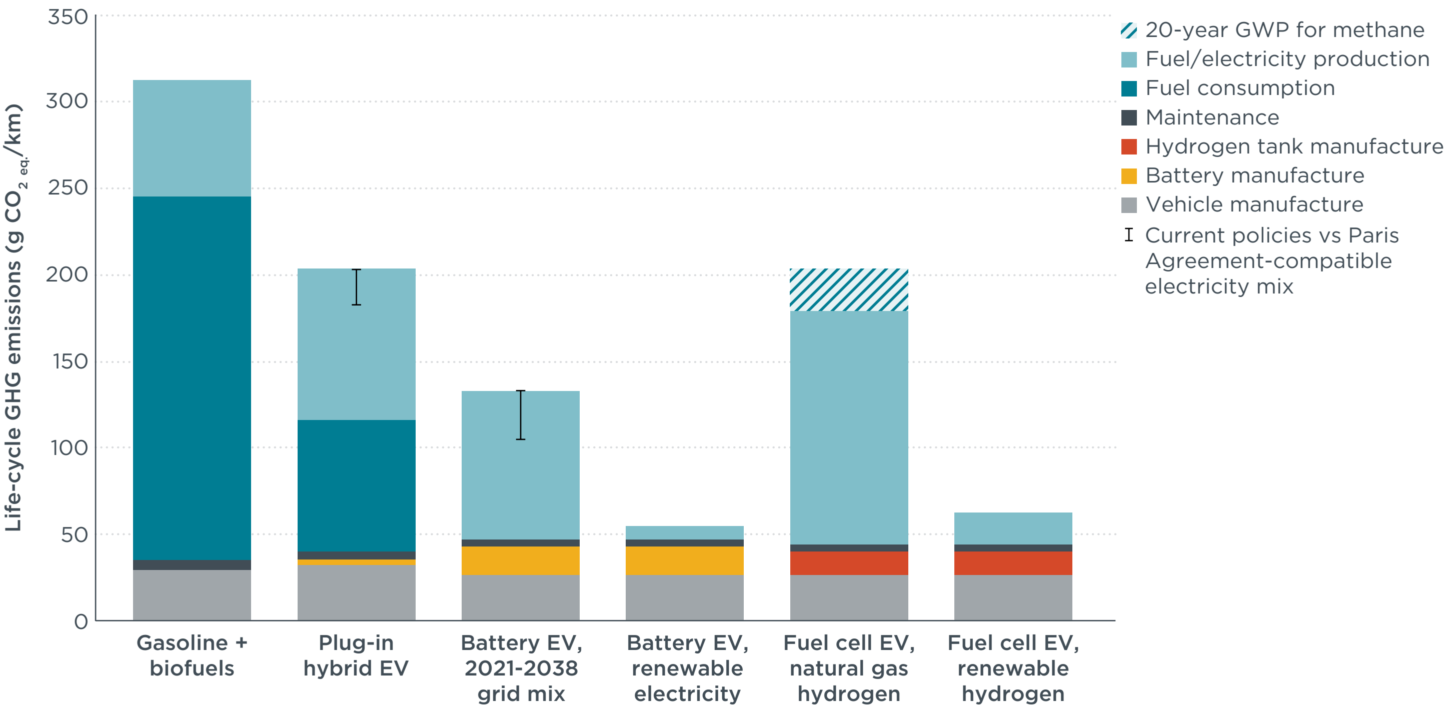

Figure 4.2. Life-cycle GHG emissions of SUV segment gasoline ICEVs, PHEVs, BEVs, and FCEVs registered in the United States in 2021.

Gasoline vehicles in the United States show higher fuel consumption than in other regions

The life-cycle GHG emissions of average new gasoline ICEVs are estimated as 254 g $CO_{2\ eq.}$/km for passenger cars and 312 g $CO_{2\ eq.}$/km for SUVs. These values are higher than in other regions mostly due to the high average real-world fuel consumption of 7.8 L/100 km (30.0 MPG) for passenger cars and 9.7 L/100 km (24.3 MPG) for SUVs (EPA, 2021).

Corn ethanol in the U.S. gasoline blend corresponds to high land use change emissions

With direct production emissions of 46 g $CO_{2\ eq.}$/MJ (Argonne National Laboratory, 2020) and ILUC emissions of 26 g $CO_{2\ eq.}$/MJ (EPA, 2010), U.S. corn ethanol is considered with life-cycle GHG emissions of 73 g $CO_{2\ eq.}$/MJ, which is only 22% lower than for the 93 g $CO_{2\ eq.}$/MJ for fossil gasoline (EPA, 2010). Thereby, similar to the E5 ethanol blend in Europe, the life-cycle GHG emissions of the U.S. E10 gasoline blend is only 2% lower than fossil gasoline. The nominal reduction in direct combustion emissions (TTW) is essentially offset by higher fuel production emission (WTT).

PHEVs correspond to 35%–46% lower life-cycle GHG emissions than gasoline cars

For the two representative PHEV models, the Honda Clarity and the Mitsubishi Outlander, the average fuel consumption values reported by users of the EPA's website MyMPG (EPA & U.S. Department of Energy, 2021) are combined with the respective proportion of the EPA's electricity consumption values (EPA & U.S. Department of Energy, 2020). Depending on whether the development of the electricity mix is considered with the IEA's STEPS or the SDS, this corresponds to life-cycle GHG emissions of 136–148 g $CO_{2\ eq.}$/km for the passenger cars and 182–203 g $CO_{2\ eq.}$/km for SUVs, which is 35-46% lower than for the respective gasoline cars.

Compared to Europe and China (below), the relative GHG emissions benefit of PHEVs is higher in the United States. Two factors account for this. One, average gasoline vehicles in the United States have high fuel consumption and thus high GHG emissions. Two, the average real-world electric drive share of PHEVs in the United States is higher than in Germany or China (Plötz et al., 2020).

BEVs correspond to 57%–68% lower life-cycle GHG emissions than gasoline cars

The life-cycle GHG emissions of average new BEVs in the United States are estimated to be 83–103 g $CO_{2\ eq.}$/km for the passenger car and 105–133 g $CO_{2\ eq.}$/km for the SUV segment, depending on whether the IEA's STEPS or SDS is considered. These values are 57%–68% lower than for the respective gasoline cars. Despite the higher carbon intensity of the average U.S. power grid (compare **Figure 2.1**), the relative GHG emissions benefit of BEVs compared to average gasoline vehicles is similar to that in Europe. This is mostly because the fuel consumption of gasoline vehicles in the United States is also higher.

FCEVs are only low carbon when using CCS or renewable electricity-based hydrogen

With the EPA hydrogen consumption in **Table A.4** (EPA & U.S. Department of Energy, 2020) and the carbon intensities of the different hydrogen pathways in the United States in **Table A.22** (Argonne National Laboratory, 2020), FCEVs using only renewable electricity-based hydrogen correspond to 54 g $CO_{2\ eq.}$/km for the passenger car segment and 62 g $CO_{2\ eq.}$/km for the SUV segment. These values are 79%–80% lower than for gasoline cars and only slightly higher than the emissions levels of 46 g $CO_{2\ eq.}$/km and 54 g $CO_{2\ eq.}$/km for using renewable electricity in BEVs.

However, FCEVs using hydrogen produced from natural gas correspond to 153 g $CO_{2\ eq.}$/km for the passenger car segment and 179 g $CO_{2\ eq.}$/km for the SUV segment, which is only 40%–43% lower than the emissions of average gasoline cars. When considering the 20-year GWP of the upstream methane leakage emissions of natural gas production, the GHG emission impact is at 174 g $CO_{2\ eq.}$/km and 204 g $CO_{2\ eq.}$/km, which is only 31%–35% lower than for gasoline vehicles.

When considering the use of CCS to offset parts of the GHG emissions of natural-gas derived hydrogen, the life-cycle GHG emissions of FCEVs are estimated at 78 g $CO_{2\ eq.}$/km and 91 g $CO_{2\ eq.}$/km for the 100-year GWP and at 99 g $CO_{2\ eq.}$/km and 116 g $CO_{2\ eq.}$/km for the 20-year GWP. These emissions are 69%–71% lower than for gasoline cars for the 100-year GWP and 61%–63% lower for the 20-year GWP.

4.2 2030 PASSENGER CARS

Data and assumptions

The 2017 *Corporate Average Fuel Economy* (CAFE) standards called for a reduction of the average official fuel consumption of passenger cars and light trucks of 5% per year in 2020–2025 (EPA & U.S. Department of Transportation, 2012), but were substantially weakened to a rate only 1.5% per year in the period of 2021–2026 by the 2020 *Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule* (EPA & U.S. Department of Transportation, 2020). According to this rate, the average official fuel consumption of passenger cars and light trucks in 2026 would need to be 9% lower than their respective 2020 levels. Continuing the trend to 2030 would correspond to a reduction of 14%. Due to off-cycle and other credits, however, the reduction in real-world usage is expected to be lower (Isenstadt & Lutsey, 2020). Therefore, the real-world fuel consumption of average gasoline passenger cars and SUVs registered in 2030 would need to be only about 10% lower than what is considered for 2021 vehicles. The *Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule* is currently being reviewed and could be replaced by more stringent targets.

In parallel, zero-emission vehicle (ZEV) regulations in California and a growing number of states foresee increasing sales of BEVs, PHEVs, and FCEVs.[8] With an expected increase of the combined share of BEVs, FCEVs, and PHEVs in these states to only about 8% by 2025 (California Air Resources Board, 2017), any such ZEV regulations are not considered to, on their own, largely increase ZEV sales shares on a national level.

The decreasing costs of battery production are considered to result in 20% higher battery capacities of BEVs and PHEVs. This partly offsets the GHG emission benefits of a shift to NMC811-graphite batteries, domestic production, and overall improvements in battery production technology. For PHEVs, the higher capacity is considered to directly translate into a higher electric drive share and thus lower fuel consumption (Plötz et al., 2020). In the absence of policies that reduce the average electricity and hydrogen consumption of BEVs and FCEVs, those are considered to remain at today's levels. While the gasoline fuel blend is considered to remain at today's level also during the lifetime of 2030 cars, the GHG emissions intensity of the average electricity production mix continues to follow the IEA's STEPS and SDS projections.

8 Adopted in California, Colorado, Connecticut, Maine, Maryland, Massachusetts, New York, New Jersey, Oregon, Rhode Island, and Vermont. Washington has passed its legislation and is in the process of adopting. These correspond to about 32% of new car sales in the United States. Legislation and adoption steps are also underway in other states, e.g., Minnesota and New Mexico.

LCA results and discussion

As illustrated in Figures 4.3 and 4.4, the lower fuel consumption and lower carbon intensity of vehicle production reduce the life-cycle GHG emissions of average 2030 gasoline cars by 10% compared to 2021 gasoline cars, to 228 g $CO_{2\ eq.}$/km for the passenger car segment and 280 g $CO_{2\ eq.}$/km for the SUV segment.

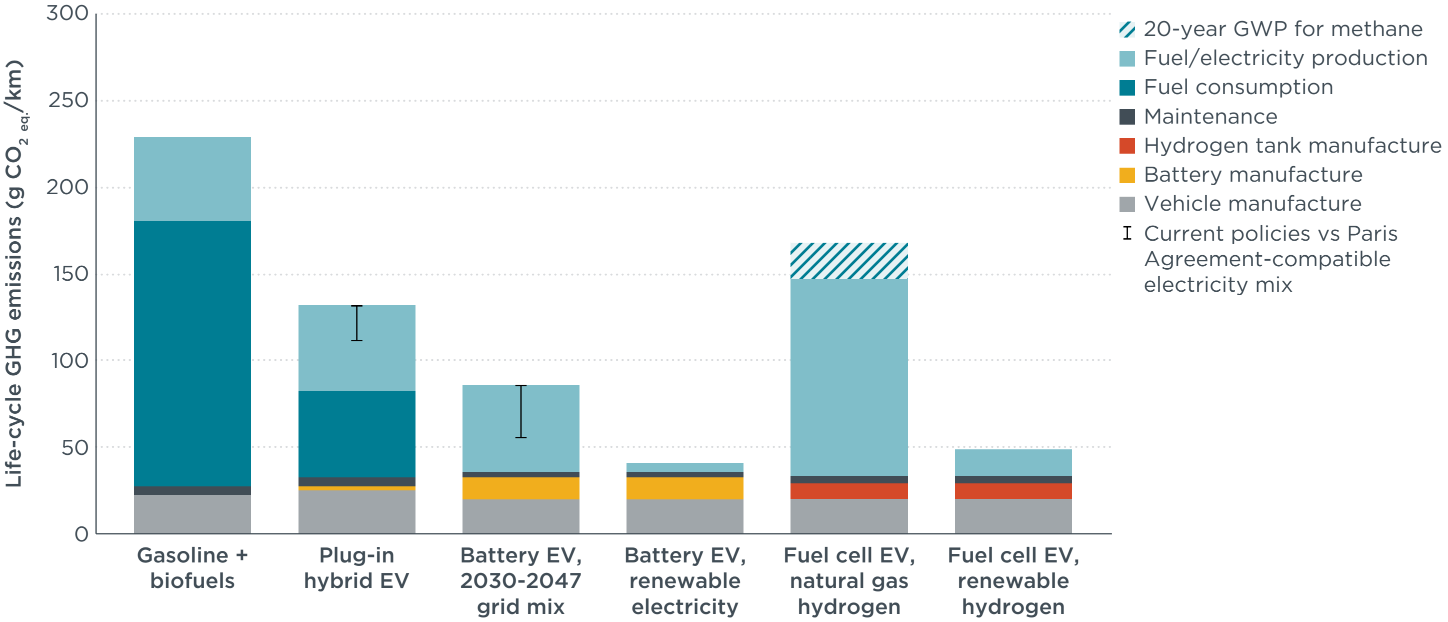

Figure 4.3. Life-cycle GHG emissions of passenger car segment gasoline ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in the United States in 2030.

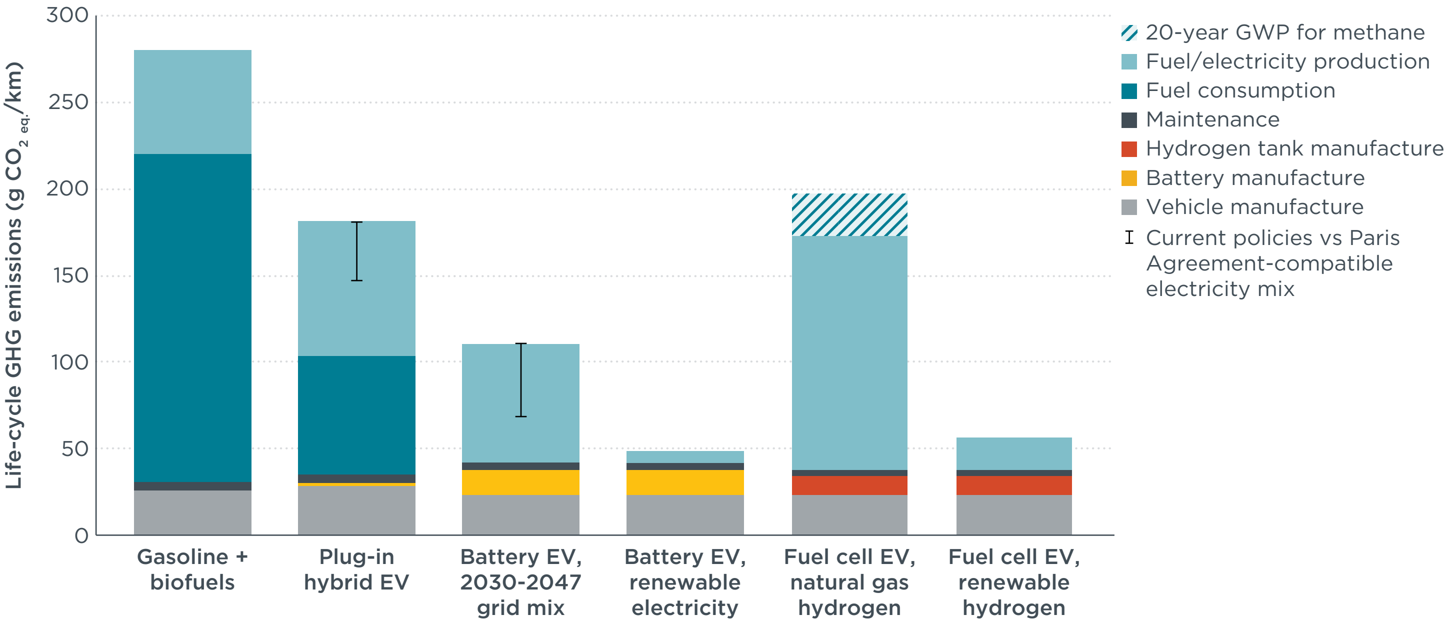

Figure 4.4. Life-cycle GHG emissions of SUV segment gasoline ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in the United States in 2030.

The GHG emissions benefit of PHEVs over gasoline cars remains similar to that of 2021 vehicles

With the assumption of a higher 20% electric range, the electric drive share of hypothetical 2030 versions of the Honda Clarity and Mitsubishi Outlander are estimated to increase by 5%.[9] For both models, this would correspond to about 10% lower fuel consumption and 10% higher electricity consumption. Including the lower GHG emissions of the U.S. average electricity mix, the life-cycle GHG emissions of passenger car and SUV segment PHEVs are 11%–19% lower than for current PHEVs, at 111–131 g $CO_{2\ eq.}$/km and 14–181 g $CO_{2\ eq.}$/km, respectively. Compared to the emissions of respective 2030 average gasoline vehicles, the life-cycle GHG emissions of PHEVs are 35%–42% lower for a development of the electricity mix according to the STEPS and 47%–51% lower for the SDS. This relative GHG emissions benefit for PHEVs over gasoline cars is similar to that of 2021 cars.

2030 BEVs correspond to 61%–76% lower life-cycle GHG emissions than gasoline cars

The life-cycle GHG emissions of BEVs registered in 2030 are 17%–35% lower than for 2021 BEVs, depending on whether the STEPS or the SDS electricity mix projections are considered. For 2030 cars, they are 56–86 g $CO_{2\ eq.}$/km for passenger cars and 68–110 g $CO_{2\ eq.}$/km for SUVs, and thereby 61%–76% lower than 2030 gasoline vehicles.

All three hydrogen pathways remain at similar emission levels as for 2021 cars

With only minor changes in the vehicle and hydrogen system production emissions, the life-cycle GHG emissions of FCEVs in the passenger car and SUV segments are similar levels to those for 2021 cars, at 48–56 g $CO_{2\ eq.}$/km for green hydrogen, 72–84 g $CO_{2\ eq.}$/km for blue hydrogen, and 147–172 g $CO_{2\ eq.}$/km for grey hydrogen. Considering the 20-year GWP, the life-cycle emissions of blue and grey hydrogen-powered FCEVs are at 93–109 g $CO_{2\ eq.}$/km and 168–197 g $CO_{2\ eq.}$/km, respectively. Thereby, also the relative GHG emissions impact compared to 2030 gasoline cars remains the same as for 2021 cars.

4.3 SUMMARY AND CONCLUSIONS

For U.S. passenger cars and SUVs, only BEVs and FCEVs offer a deep reduction of the life-cycle GHG emissions compared to today's gasoline vehicles. Same as the results showed for Europe, however, FCEVs require either relatively large amounts of renewable energy or to rely on CCS in order to be a low-carbon powertrain type. BEVs, meanwhile, offer a high GHG emissions benefit even when powered by grid average electricity. For gasoline vehicles, which may also include an increasing share of HEVs, the fleet-wide reduction in fuel consumption expected from adopted and stated policies would only slightly reduce their high GHG emissions. For the U.S. biofuel blend, it is found that the high ILUC and production emissions of corn ethanol effectively offset the nominal reduction in combustion emissions. PHEVs show a higher relative GHG emissions reduction potential than in Europe or China, but depending on the development of the electricity mix, their life-cycle GHG emissions remain up to twice as high as for BEVs.

BEVs

The life-cycle GHG emissions of U.S. average BEVs registered in 2021 are 57%–68% lower than for comparable average gasoline vehicles. It is notable that these numbers correspond to the carbon intensity of the national average U.S. grid; in states like California, where the carbon intensity of electricity is below the national average, the life-cycle GHG emissions of BEVs would also be lower.

9 A 20% higher battery capacity is assumed to increase the EPA electric range of the Honda Clarity (17 kWh variant) from 77 km to 92 km, and the Mitsubishi Outlander (12 kWh variant) from 35 km to 42 km. Thereby, the electric drive shares of the Honda Clarity and the Mitsubishi Outlander are estimated to increase from 55% to 60%, and from 63% to 68%, respectively (Plötz et al., 2020).

For BEVs projected to be registered in 2030, this study finds that the life-cycle GHG emissions are 61%–76% lower than what is expected from 2030's gasoline vehicles. As depicted in **Figure 2.1**, the projected development of the U.S. electricity mix in the STEPS deviates fairly significantly from what the SDS estimates to be required in order to support Paris Agreement goals. With this, the range of GHG emissions expected from today's and future BEVs is larger in the United States than in the European Union, for instance. Even for the STEPS electricity mix, though, U.S. BEVs offer a substantial reduction of life-cycle GHG emissions compared to gasoline vehicles and PHEVs. For BEVs registered after 2030, the GHG emissions impact would approach the levels of driving them only on renewable electricity, which is more than 80% lower than the emissions of today's gasoline vehicles.

FCEVs

When powered by natural gas-based hydrogen, FCEVs only show slightly lower life-cycle GHG emissions than gasoline vehicles, especially when considering the 20-year GWP of upstream methane emissions. For a deep reduction of GHG emissions similar to what is achievable with BEVs, parts of hydrogen production emissions need to be offset by CCS or in the best case, hydrogen needs to be produced entirely from renewable energy sources.

As in Europe, the energy demand of driving on renewable electricity-based hydrogen is about three times higher than directly using the electricity in BEVs. While renewable energy capacities remain limited, the availability of renewable electricity for less efficient technologies is a concern. Also, in order to not divert the renewable electricity from an existing use, it must be ensured that the used renewable energies for hydrogen production are delivered by new, additional power plants.

PHEVs

PHEVs in the United States tend to be driven more on electricity than PHEVs in Europe or China (Plötz et al., 2020). Because their gasoline car counterparts also have higher fuel consumption, the relative GHG emissions benefit of U.S. PHEVs is higher than in Europe or China. For PHEVs registered in 2021, the life-cycle GHG emissions are estimated to be 35%–46% lower than for 2021 gasoline vehicles. With a higher electric drive share and the decarbonization of the electricity mix, the life-cycle GHG emissions of PHEVs projected to be registered in 2030 are expected to decrease, but only to a similar level as that of average gasoline vehicles, as those are also assumed to improve.

Compared to average BEVs, however, the GHG emissions of today's PHEVs are 43%–73% higher. For vehicles projected to be registered in 2030, this gap increases to 53%–116%.

Biofuels

As the U.S. ethanol blend is almost entirely based on corn ethanol, its production and ILUC emissions are only 22% lower than for fossil gasoline (Malins & Searle, 2019). Thereby, even at a high blend rate of 10vol.%, it reduces the carbon intensity of the fuel mix by only 2%.

For more significant reductions of GHG emissions, the U.S. biofuel policy would need to reduce the amount of food-based, first generation biofuels and focus on advanced, waste- and residues-based feedstocks, instead. Moreover, as discussed in the Europe section, low-carbon biofuels would eventually be limited by feedstock availability and/or production costs, and the production capacities would need time to scale up. Finally, the use of low-carbon biofuels in other sectors of transportation like aviation (Pavlenko, 2021; O'Malley et al., 2021) and shipping (Zhou et al., 2020) will reduce the volumes available for passenger cars.

5 CHINA

With about 21 million new car registrations in 2019, the Chinese car market is larger than the U.S. or European markets. While data from China Automotive Technology and Research Center and China Association of Automobile Manufacturers shows that most of these cars are powered by gasoline—94.2% in 2019, including 1.5% HEVs—new energy vehicles (NEVs) were also registered in notable amounts. NEVs are BEVs, which were 3.9% in 2019, PHEVs, 1.0% in 2019, and FCEVs, 0.0% in 2019. For 2025, the *NEV Industrial Development Plan 2021–2035* sets the target of 20% of new passenger and commercial vehicles to be NEVs (China State Council, 2020). To compensate for a lower share of NEVs in other vehicle segments, this might require an even higher share of passenger car NEVs. For 2030 and 2035, a recent technology roadmap led by the Society of Automotive Engineering China (China Society of Automotive Engineers, 2020) informally proposed NEV shares of 40% and 50%, respectively. These shares would be lower than in Europe, where the ZLEV benchmark is considered to result in BEV and PHEV shares of 27% each in 2030 (Buysse et al., 2021).

Estimates of the life-cycle GHG emissions of gasoline cars, PHEVs, BEVs, and FCEVs are based on average real-world characteristics in the SUV segment, which was 44.2% of new registrations in 2019, the medium-size A segment, 30.6%, and the small-size A0 segment, 4.4% (data from China Automotive Technology and Research Center).

5.1 2021 PASSENGER CARS

Data and assumptions

The following paragraphs summarize the factors that most influenced the analysis. All data and assumptions are discussed in the Appendix.

For gasoline cars, the fuel consumption is based on the sales-weighted NEDC values of cars registered in 2019 (data from China Automotive Technology and Research Center). With an average deviation of user-reported to NEDC fuel consumption values of 34% (Yang & Yang, 2018), these are adjusted to real-world driving conditions. For BEVs, the battery capacity corresponds to the segment-specific averages of new cars in 2019 (data from China EV100). With the corresponding average NEDC range, assumptions on the real-world deviation, and charging losses, the average real-world electricity consumption is estimated (**Table A.6**). PHEVs are represented by the Roewe ei6 and the BYD Song, because their average consumer-reported fuel consumption is found to be similar to the sales-weighted average of consumer-reported values for PHEVs in the A and SUV segments, respectively (Plötz et al., 2020). Similar to BEVs, the corresponding real-world electricity consumption is estimated based on the battery capacity, the NEDC range, and assumptions about the real-world deviation and charging losses (**Table A.7**). FCEVs are represented by the Toyota Mirai in the A segment and Hyundai Nexo in the SUV segment, both with the hydrogen consumption values provided by the ADAC Ecotest (Allgemeiner Deutscher Automobil-Club, 2021).

The average gasoline blend is considered with an ethanol share of about 5%, which is entirely based on corn (U.S. Department of Agriculture, 2020). The development of the average electricity mix is based on the IEA's Stated Policy Scenario (STEPS) and compared to the Sustainable Development Scenario (SDS; IEA, 2020). In a conservative approach, the analysis considers that cars registered in China in 2021 will be used for 15 years (Hao et al., 2011; China Automotive Technology and Research Center, 2017).

With an average annual mileage of 19,000 km/a (China Automotive Technology and Research Center, 2017; Liu et al. 2017; Huo et al., 2012) the lifetime mileage amounts to 285,000 km. For A0 segment cars, the annual mileage is assumed to be 10% lower, resulting in a lifetime mileage of 256,500 km.

LCA results and discussion

Figures 5.1 to 5.3 present the life-cycle GHG emissions in g $CO_{2\ eq.}$/km of gasoline ICEVs, BEVs, PHEVs, and FCEVs in the applicable segments. For the vehicle production, the GHG emissions of the battery and of the hydrogen system, which itself combines a hydrogen tank and a fuel cell, are distinguished from the production of the rest of the vehicles. The use phase corresponds to GHG emissions of fuel and electricity production (WTT), fuel consumption in the vehicle (TTW) and maintenance.

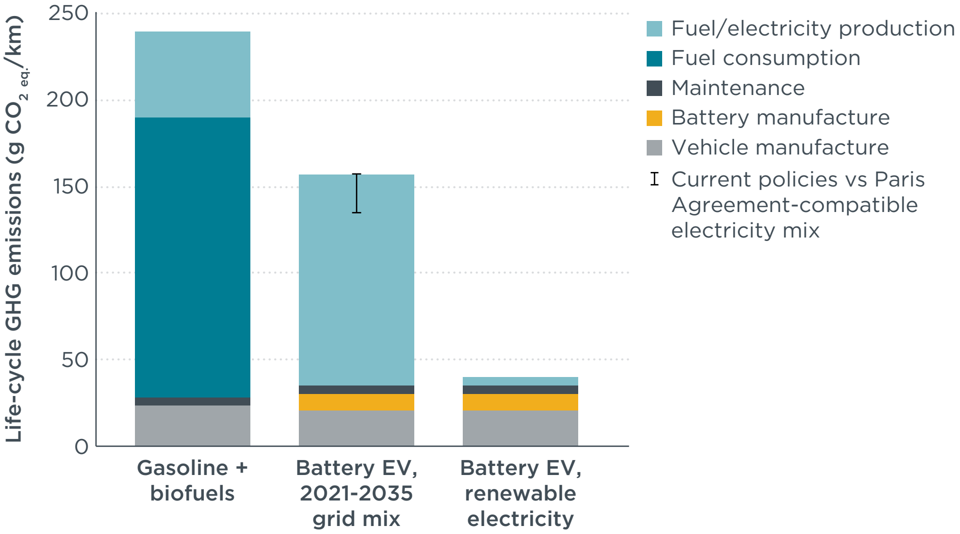

Figure 5.1. Life-cycle GHG emissions of A0 segment gasoline ICEVs and BEVs registered in China in 2021.

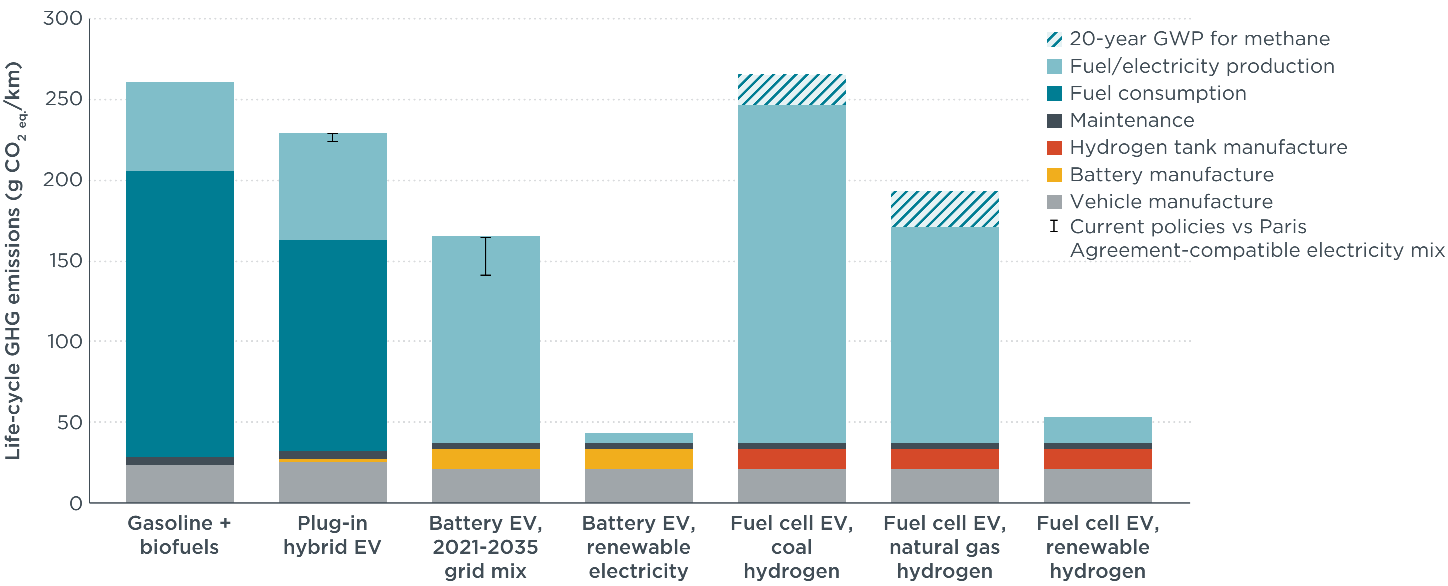

Figure 5.2. Life-cycle GHG emissions of A segment gasoline ICEVs, PHEVs, BEVs, and FCEVs registered in China in 2021.

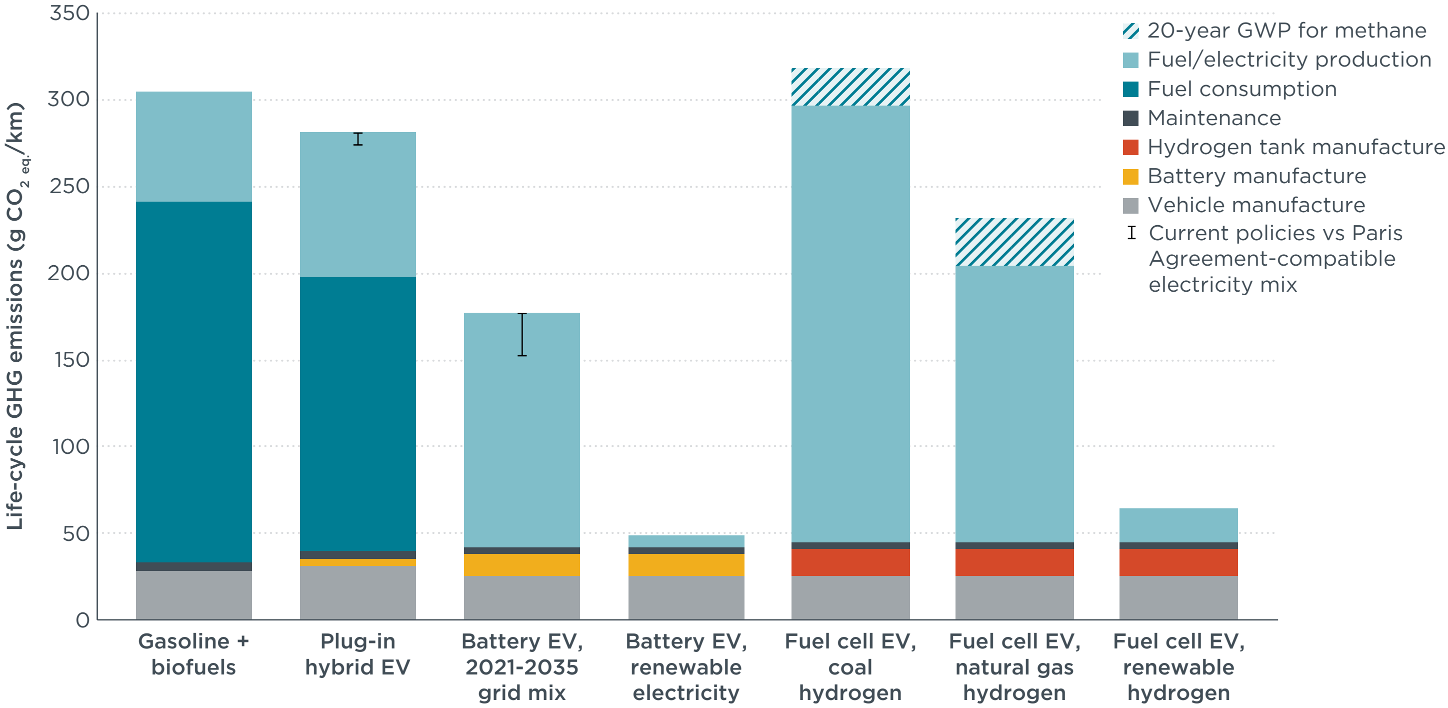

Figure 5.3. Life-cycle GHG emissions of SUV segment gasoline ICEVs, PHEVs, BEVs, and FCEVs registered in China in 2021.

Gasoline cars in China have high fuel consumption and therefore high GHG emissions

Average new gasoline cars in China show real-world fuel consumption of 7.2 L/100 km for A0 segment cars, 7.9 L/100 km for A segment cars, and 9.2 L/100 km for SUVs (**Table A.6**). For A segment cars and SUVs, the fuel consumption is similar to passenger cars and SUVs in the United States (**Table A.4**), but 10%–16% higher than the fuel consumption of the average lower medium and SUV segment gasoline cars in Europe (**Table A.2**). New gasoline vehicles in China correspond to comparably high life-cycle GHG emissions of 239 g $CO_{2\ eq.}$/km for the A0 segment, 260 g $CO_{2\ eq.}$/km for the A segment, and 305 g $CO_{2\ eq.}$/km for SUVs.

In real-world usage, PHEVs correspond to only 8%–14% lower emissions than gasoline cars

The average user-reported fuel consumption of PHEVs in China is found to be about 4 times higher than indicated by NEDC values (Plötz et al., 2020). In addition to a higher fuel consumption of the combustion engine and a lower range when driving on electricity, this high deviation mostly corresponds to a lower charging frequency than the one full recharge per driving day that is assumed in the NEDC values. With 5.8 L/100 km for the Roewe ei6 and 7.0 L/100 km for the BYD Song, the average user-reported fuel consumption of these two models is found to be representative for the 2019 sales-weighted average of the PHEV models in China. These values are estimated to correspond to an electric drive share of only 17%–21%, which is similar to the electric drive share estimated for other models in China (Plötz et al., 2020).[10] When including the respective portion of driving on electricity, the life-cycle GHG emissions are 224–229 g $CO_{2\ eq.}$/km for A segment PHEVs and 275–281 g $CO_{2\ eq.}$/km for SUV segment PHEVs, depending on whether the electricity mix is considered to develop according to the IEA's STEPS or SDS. These values correspond to only 8%–14% lower life-cycle GHG emissions than the respective segments' average gasoline cars.

10 Note that the electric drive share considered here is a different measure than the share of driving in the mixed combustion engine and electric CD drive mode that is used in the Europe part of the analysis.

The relatively low small GHG emissions benefit of PHEVs compared to gasoline vehicles results from two factors: (1) the low electric drive share; and (2) the high carbon intensity of the electricity grid in China. Under ideal usage conditions, which would imply that PHEVs are charged once on each driving day, the electric range would be as high as considered in official test values and the electric drive share would correspond to what is considered in the NEDC values. Weighting the real-world fuel and electricity consumption in combustion engine and electric driving as provided in **Table A.7** by the NEDC electric drive shares of 68% for the Roewe ei6 and 76% for the BYD Song would result in life-cycle GHG emission values of 182–200 g $CO_{2\ eq.}$/km for the A segment and 206–229 g $CO_{2\ eq.}$/km for the SUV segment. Even under such ideal use conditions, PHEVs would thus only correspond to 23%–32% lower life-cycle GHG emissions than gasoline cars.

BEVs correspond to about 34%–46% lower life-cycle GHG emissions than gasoline cars

With a high share of coal power in the average electricity mix in China, the life-cycle GHG emissions from electricity production are significantly higher than in Europe or the United States (compare **Figure 2.1**). Thereby, average new BEVs in the A0, A, and SUV segments in China correspond to life-cycle GHG emissions of 135–157 g $CO_{2\ eq.}$/km, 142–165 g $CO_{2\ eq.}$/km and 153–177 g $CO_{2\ eq.}$/km, depending on whether the electricity mix is considered to develop according to STEPS or the SDS. Thus for the STEPS projections of the electricity mix, BEVs correspond to 34%–42% lower life-cycle GHG emissions than average gasoline cars, and under the SDS, they are 44%–46% lower than gasoline cars.

When driving BEVs only on renewable electricity, the life-cycle GHG emissions correspond to 40–48 g $CO_{2\ eq.}$/km, which is 83%–84% lower than for gasoline cars.

FCEVs are only low carbon when using CCS or renewable electricity-based hydrogen

Today, a large share the hydrogen in China is black hydrogen, which is produced from coal gasification (China EV100, 2020; IEA, 2019).[11] With 175 g $CO_{2\ eq.}$ per MJ (Argonne National Laboratory, 2020), coal-based hydrogen corresponds to about 60% higher GHG emissions than the 111 g $CO_{2\ eq.}$ per MJ for grey hydrogen produced from natural gas (**Table A.22**). Thereby, the life-cycle GHG emissions of A segment and SUV segment FCEVs run solely on coal hydrogen are as high as for average gasoline cars, at 247 g $CO_{2\ eq.}$/km and 296 g $CO_{2\ eq.}$/km, respectively. Note, also, that coal-based hydrogen corresponds to significant methane emissions that occur during the production of coal and the coal gasification process. When considering the 20-year GWP of these emissions, the total life-cycle GHG emissions of A segment and SUV segment FCEVs are at 265 g $CO_{2\ eq.}$/km and 317 g $CO_{2\ eq.}$/km, respectively.

For driving on natural gas-derived hydrogen (grey hydrogen), the life-cycle GHG emissions are estimated as 171 g $CO_{2\ eq.}$/km for the A segment and 205 g $CO_{2\ eq.}$/km for SUVs. These values are 33%–34% lower than the life-cycle GHG emissions of gasoline cars. When considering the 20-year GWP of the methane emissions during natural gas production and transport, they are at 193 g $CO_{2\ eq.}$/km and 232 g $CO_{2\ eq.}$/km, which is 24%–26% lower than for gasoline cars.

Offsetting a share of the GHG emissions of producing hydrogen through CCS could reduce the carbon intensity of natural gas-based hydrogen to 35 g $CO_{2\ eq.}$/MJ (**Table A.22**). Thereby, the life-cycle GHG emissions of FCEVs in China would be at 79 g $CO_{2\ eq.}$/km for the A segment and 95 g $CO_{2\ eq.}$/km for SUV, which corresponds to

11 In addition, byproduct hydrogen is a relevant pathway in the hydrogen mix in China (China EV100, 2020). As it is not scalable and thus might only play a role in the mid-term, it is not considered in this study.

69%–70% lower emissions than gasoline cars. When considering the 20-year GWP of the upstream methane emissions, the GHG emissions are estimated at 91 g $CO_{2\ eq.}$/km and 122 g $CO_{2\ eq.}$/km, which corresponds to 60%–61% lower life-cycle GHG emissions than gasoline cars.

For hydrogen produced from renewable electricity (green hydrogen), the life-cycle carbon intensity is estimated at only 14 g $CO_{2\ eq.}$ per MJ (**Table A.22**). Thereby, for FCEVs driving only on renewable electricity-based hydrogen, the life-cycle GHG emissions are at 53 g $CO_{2\ eq.}$/km for A segment cars and 64 g $CO_{2\ eq.}$/km for SUVs, and correspond to 79%–80% lower levels than gasoline cars.

5.2 2030 PASSENGER CARS

Data and assumptions

When combining the preliminary fuel efficiency target of 3.2 L/100km (NEDC), as outlined by the national strategic plan *Made in China 2025* (Ministry of Industry and Information Technology, 2015), with an NEV share of 40% as proposed by the SAE (China Society of Automotive Engineers, 2020), the average NEDC fuel consumption of gasoline cars registered in 2030 is estimated to be reduced to 5.2 L/100 km (Yang & Cui, 2020). This is about 20% lower than the average NEDC values for 2019. With the assumption that the deviation between real-world and official test values remains constant, this study also considers the real-world fuel consumption to decrease by 20%.

For BEVs registered after 2025, the *NEV Industrial Development Plan 2021–2035* (China State Council, 2020) requires an average energy efficiency of 12 kWh/100 km in the China light-duty vehicle test cycle (CLTC). Since the CLTC is similar to the WLTP, the real-world electricity consumption is assumed to exceed these values by the same 19% as considered for the WLTP electricity consumption values in Europe (Allgemeiner Deutscher Automobil-Club, 2021). Thereby, the real-world electricity consumption of future BEVs in China would be 30% lower than today. In parallel, due to decreasing battery production costs, the capacities of the batteries in BEVs and PHEVs are assumed to be 20% higher than today. For PHEVs, the respective increase in the electric range is considered to increase the real-world electric drive share and thereby reduce the average fuel consumption (Plötz et al., 2020).

Finally, a continuous reduction of the share of coal power plants in the average electricity mix (IEA, 2020) lowers the life-cycle GHG emissions of PHEVs and BEVs. The average gasoline blend, in contrast, is considered to remain constant.

LCA results and discussion

As presented in Figures 5.4 to 5.6, the 20% lower fuel consumption decreases the life-cycle GHG emissions of average gasoline cars to 193 g $CO_{2\ eq.}$/km for A0 segment cars, 210 g $CO_{2\ eq.}$/km for A segment cars, and 246 g $CO_{2\ eq.}$/km for SUVs. These correspond to 19% lower life-cycle GHG emissions than the respective gasoline cars in 2021.

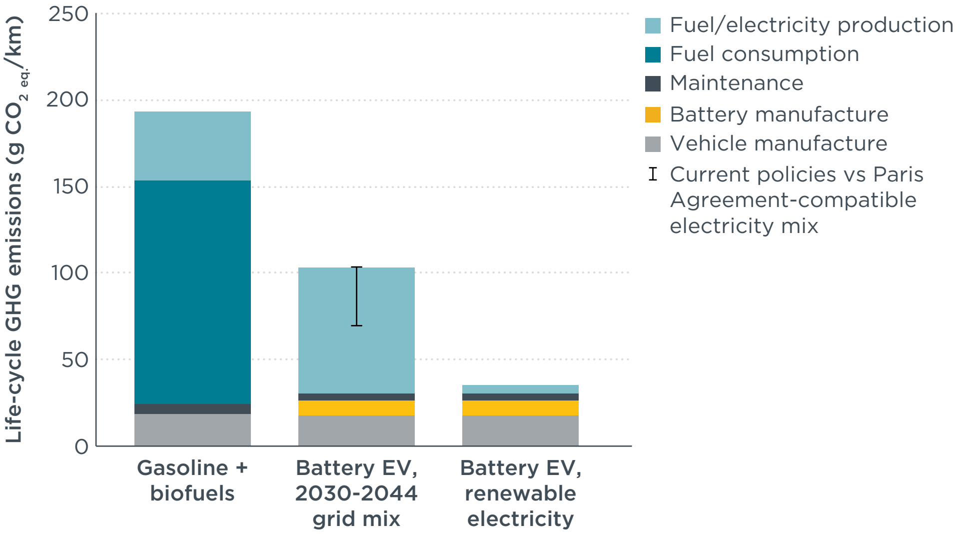

Figure 5.4. Life-cycle GHG emissions of A0 segment gasoline ICEVs and BEVs projected to be registered in China in 2030.

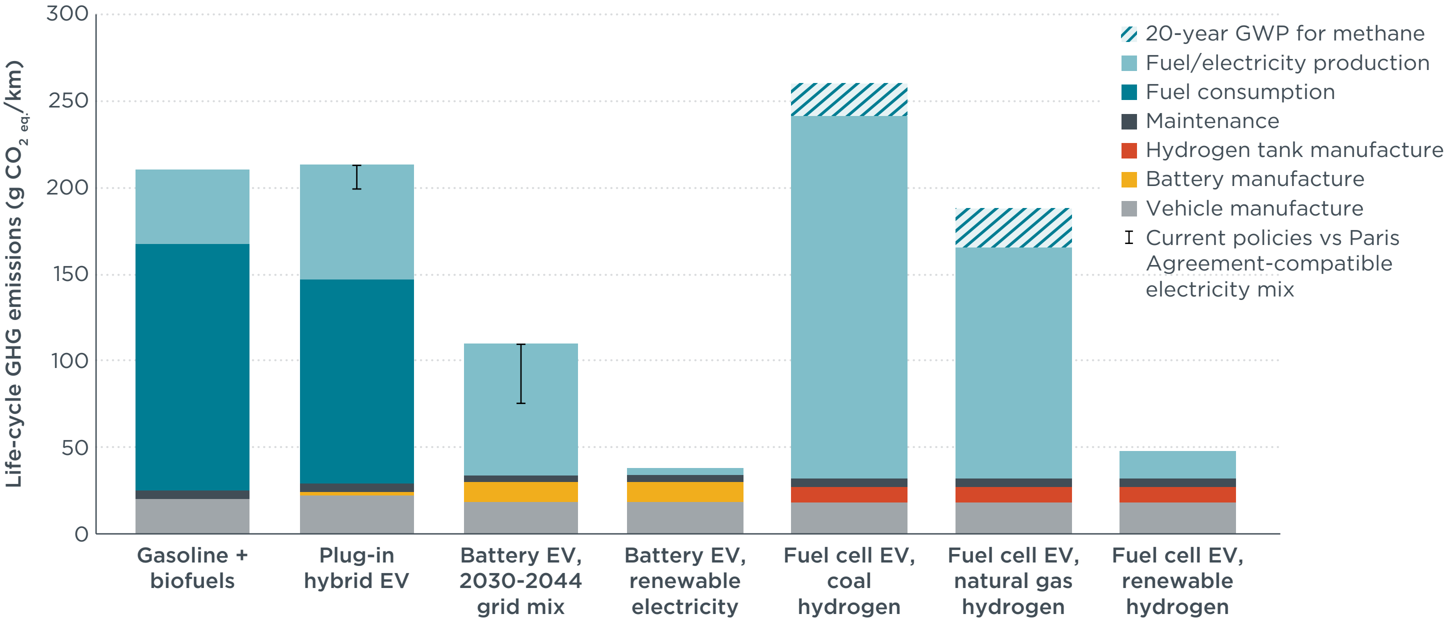

Figure 5.5. Life-cycle GHG emissions of A segment gasoline ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in China in 2030.

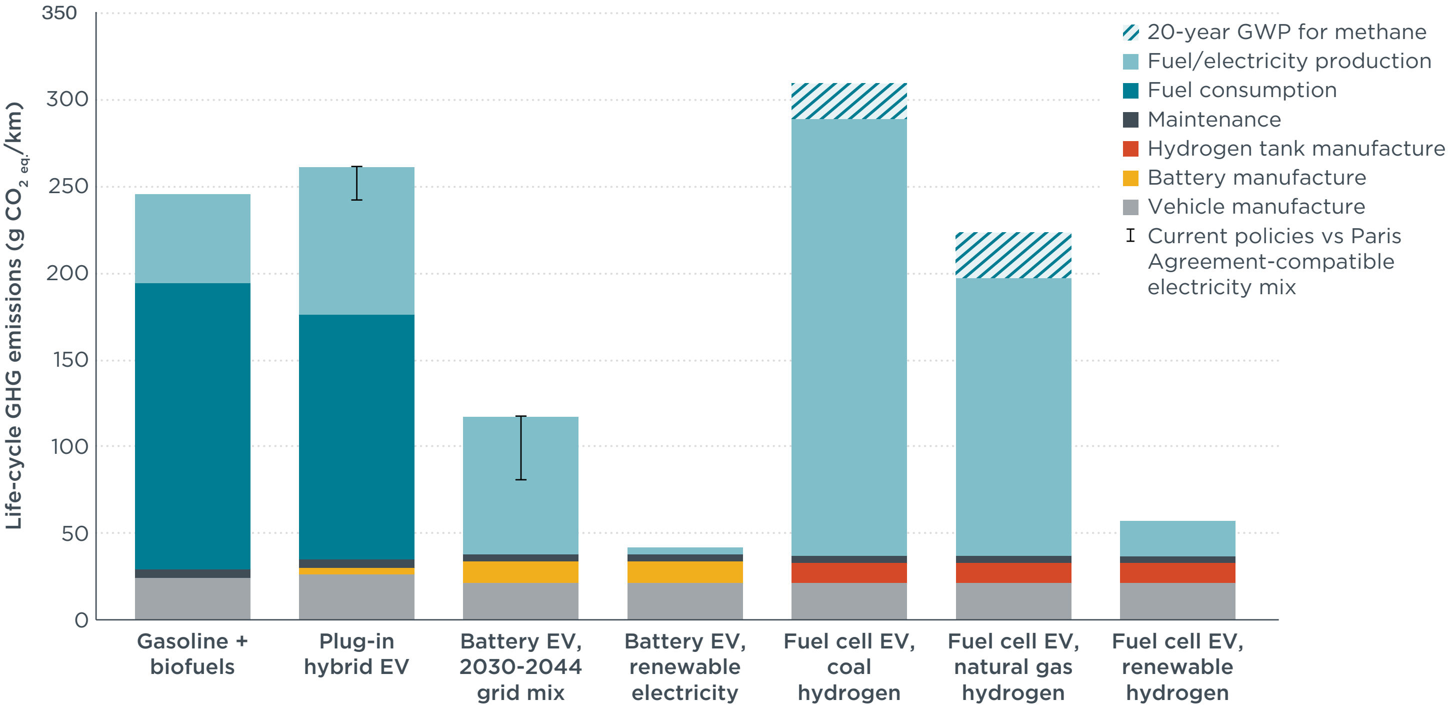

Figure 5.6. Life-cycle GHG emissions of SUV segment gasoline ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in China in 2030.

PHEVs have only 7%–12% lower emissions than 2021, and are similar to gasoline cars

With an increased electric range, the real-world electric drive share of PHEVs registered in 2030 is considered to increase from 17% to 25% for the A segment and from 21% to 29% for the SUV segment. This implies a 10% lower fuel and a 40% higher electricity consumption (compare **Table A.7**) and results in life-cycle GHG emissions of 199–213 g $CO_{2\ eq.}$/km for A segment cars and 243–262 g $CO_{2\ eq.}$/km for SUVs. These values are only 7%–12% lower than for current PHEVs, and as the GHG emissions of average gasoline cars are considered to decrease much more than that, future PHEVs would not offer a GHG emission benefit.

BEVs correspond to 46%–67% lower GHG emissions than gasoline cars

Due to lower electricity consumption and a less coal-intensive electricity mix, the life-cycle GHG emissions of BEVs registered in 2030 are 34%–47% lower than for BEVs registered in 2021. They correspond to 70–103 g $CO_{2\ eq.}$/km for A0 segment cars, 74–109 g $CO_{2\ eq.}$/km for A segment cars, and 81–118 g $CO_{2\ eq.}$/km for SUVs, depending on whether the STEPS or SDS projections are considered. For the STEPS projections, these values are 46%–52% lower than the life-cycle GHG emissions of 2030 gasoline cars, and for SDS, they are 64%–67% lower than for gasoline cars.

For all four hydrogen pathways, the GHG emissions remain the same as for 2021 cars

For A segment and SUV segment FCEVs, respectively, life-cycle GHG emissions are estimated at 48–57 g $CO_{2\ eq.}$/km for green hydrogen, 74–88 g $CO_{2\ eq.}$/km for blue hydrogen, 165–198 g $CO_{2\ eq.}$/km for grey hydrogen, and 242–290 g $CO_{2\ eq.}$/km for black hydrogen. When considering the 20-year GWP of the methane emissions in the natural gas and coal pathways, life-cycle GHG emissions are at 98–115 g $CO_{2\ eq.}$/km for blue, 187–225 g $CO_{2\ eq.}$/km for grey, and 260–311 g $CO_{2\ eq.}$/km for black hydrogen.

Due to the lower GHG emissions of average gasoline cars in China, the relative reduction of GHG emissions from driving FCEVs on blue hydrogen compared to gasoline cars decreases to 64%–65% for the 100-year GWP and to 33%–36% for the 20-year GWP. For grey hydrogen, the relative emissions benefit compared to gasoline cars is even smaller: 20%–21% for the 100-year GWP and only 9%–11% for the 20-year GWP.

5.3 SUMMARY AND CONCLUSIONS

In China, this study finds that BEVs and FCEVs offer the lowest life-cycle GHG emissions compared to the currently dominant gasoline vehicles. While BEVs offer a large GHG emissions benefit even when powered by a coal-intensive average electricity mix, FCEVs need to be powered by renewable electricity-based hydrogen or blue hydrogen to be a low carbon technology. For PHEVs, the low electric drive share in average real-world usage results in life-cycle GHG emissions only about 10% lower than for gasoline cars.

BEVs

Due to the currently high share of coal power in the average electric grid, the GHG emissions benefit of BEVs in China is smaller than in Europe or the United States. Nevertheless, even BEVs registered in 2021 are found to correspond to 34%–46% lower life-cycle GHG emissions than average new gasoline cars. For 2030 BEVs, the life-cycle GHG emissions are 46%–67% lower than the counterpart gasoline cars. In addition to a less carbon intensive electricity mix, this 2030 estimation includes an improvement in the energy consumption of BEVs.

FCEVs

When driving on hydrogen produced from coal gasification, the life-cycle GHG emissions of FCEVs exceed the GHG emission levels of gasoline cars. Driving on natural gas-based hydrogen, in contrast, corresponds to 33%–34% or 24%–26% lower life-cycle GHG emissions than today’s gasoline cars, depending on whether the 100-year GWP or the 20-year GWP of upstream methane emissions is considered. Compared to BEVs, FCEVs driving on hydrogen produced from natural gas correspond to significantly higher emissions today, and the difference is greater when considering the lower GHG emissions of future BEVs. While for 2021 cars, the 100-year GWP of driving on natural-gas hydrogen is 50%–68% higher than the life-cycle GHG emissions of average grid-powered BEVs, the GHG emissions of these FCEVs are estimated to be more than twice as high as BEVs for cars registered in 2030. For a deep reduction of GHG emissions, the production of hydrogen from natural gas can be combined with CCS. Due to a potential leakage of CO_2 from the storage sides, however, CCS would require careful regulation and monitoring (Zhou, 2020).

FCEVs powered by hydrogen solely produced from renewable electricity correspond to the second-lowest GHG emissions of all evaluated pathways in China. Only BEVs solely powered by renewables show lower emissions. As exemplified for cars in Europe, however, driving on renewable electricity-based hydrogen corresponds to a three times higher energy demand than using the electricity in BEVs. While renewable capacities remain limited, the availability of renewable electricity for less efficient technologies is a concern (Ueckerdt et al., 2021). Also, in order to avoid diverting the renewable electricity from an existing use, it must be ensured that the used renewable energy for hydrogen production is delivered by new, additional power plants.

PHEVs

Due to their low electric drive share in average real-world usage, the life-cycle GHG emissions of PHEV in China are only about 10% lower than the levels of current gasoline cars. Compared to considerably more fuel-efficient gasoline cars in 2030, this small GHG emission benefit diminishes, even when considering an increasing electric range and thus electric drive share.

Gasoline cars

Differing from the other regions, fuel efficiency standards in China are considered to significantly reduce the fuel consumption, and therefore also the life-cycle GHG emissions, of average gasoline cars registered in 2030 (Yang & Cui, 2020). This may imply an increased share of HEVs in the gasoline car fleet.

6 INDIA

India is the fifth-largest passenger car market in the world, with 2.7 million new vehicle sales in fiscal year (FY) 2019–20 (Deo, 2021). These mostly correspond to small hatchbacks, 47% of sales in FY 2019–20, medium-size sedan segment cars, 15%, and SUVs, 27%. The large majority of these are gasoline, 67% in FY 2019–20, and diesel cars, 30% that year, but also 4% of cars sold were CNG cars. With only a few thousand BEVs registered in FY 2019–20, the share remained at the low level of 0.1%, and PHEVs and FCEVs were hardly sold at all. Nevertheless, with its commitment to the EV30@30 campaign of the Clean Energy Ministerial forum, the Government of India targets at a 30% electric vehicle share of new car registrations in 2030. This target is considered to be mostly achieved by domestically produced BEVs (Gode et al., 2021).

In parallel, the 2018 *National Policy on Biofuels* aims to significantly increase the share of ethanol and biogenic diesel in future fuel blends (Pavlenko & Searle, 2019). The biomethane share in the natural gas blend is also considered to increase (IEA, 2021). This analysis thus compares the life-cycle GHG emissions of BEVs powered by a less and less coal-dominated electricity mix with increasingly biofuel-powered gasoline, diesel, and CNG cars. In addition, the life-cycle GHG emissions of driving FCEVs on different hydrogen pathways are assessed. The different powertrain types are compared across the hatchback, sedan, and SUV segments.

6.1 2021 PASSENGER CARS

Data and assumptions

The assessment of the life-cycle GHG emissions of 2021 passenger cars was mostly determined by the following considerations. More details of data and assumptions are in the Appendix.

The fuel consumption values of gasoline, diesel, and CNG cars are based on segment-specific average Modified Indian Driving Cycle (MIDC) test values for FY 2019–20. In that year, only a few CNG cars were registered in the sedan and SUV segments, and therefore the fuel consumption considered for these segments corresponds to representative vehicles: the Maruti Dzire and the Maruti Ertiga, respectively. To better reflect the fuel consumption in real-world driving conditions, the MIDC values of the gasoline, diesel, and CNG cars are adjusted with a factor of 134%, similar to the deviation of real-world and NEDC fuel consumption values observed in Europe (Dornoff et al., 2020) and China (Yang & Yang, 2018).

With only a few different BEV models sold in India in FY 2019–20 (data from EV-Volumes), the small Tata Tigor is considered as representative of the hatchback segment and the Mahindra e-Verito and the Tata Nexon represent the sedan and SUV segments, respectively. The real-world electricity consumption of these models is estimated from the manufacturer declared battery capacity, the MIDC electric range, and assumptions of the real-world deviation and charging losses (see **Table A.8**). As for the other regions, the hydrogen consumption of sedan and SUV segment FCEVs corresponds to the ADAC Ecotest values for the Toyota Mirai and the Hyundai Nexo, respectively.

For the average gasoline blend, the share of molasses, residues, and energy-crop based ethanol is considered to continuously increase from 5% in 2020 to 20% in 2040 (**Table A.17**). In the same time frame, the share of waste-based biodiesel and HVO is considered to increase from 0% to 5% (**Table A.18**). Although the *National Policy on Biofuels* aims to reach these biofuel shares by 2030, this study considers that it will take more time to ramp up the necessary biofuel production facilities (Pavlenko & Searle, 2019). Reaching these targets by 2040 is optimistic, even.

For the natural gas blend, the share of biomethane is assumed to increase from practically 0% in 2020 to 10% in 2040 (**Table A.19**, from International Energy Agency, 2021). This biomethane is considered to be entirely based on sewage. For the development of the electricity mix in India, the IEA's Stated Policy Scenario (STEPS) is compared to the Sustainable Development Scenario (SDS; IEA, 2020).

Based on ICCT's India Emissions Model (Bansal & Bandivadekar, 2013), the analysis assumes that cars registered in India in 2021 will be used for 15 years. With a lifetime mileage of about 165,000 km for hatchback and sedan segment cars and 188,000 km for SUVs, this corresponds to an average annual mileage of 11,000 km/a and 12,533 km/a, respectively. The annual mileage is considered to decrease by 3% per year.

LCA results and discussion

Figures 6.1 to 6.3 compare the life-cycle GHG emissions (in g $CO_{2\ eq.}$/km) of gasoline, diesel, and CNG ICEVs with BEVs and FCEVs in the applicable segments. The GHG emission impact of the production of the battery and the hydrogen system, consisting of a hydrogen tank and a fuel cell, is distinguished from the production and recycling of the rest of the vehicle. In the use phase, the GHG emissions of fuel and electricity production (WTT), fuel consumption in the vehicle (TTW) and maintenance are presented.

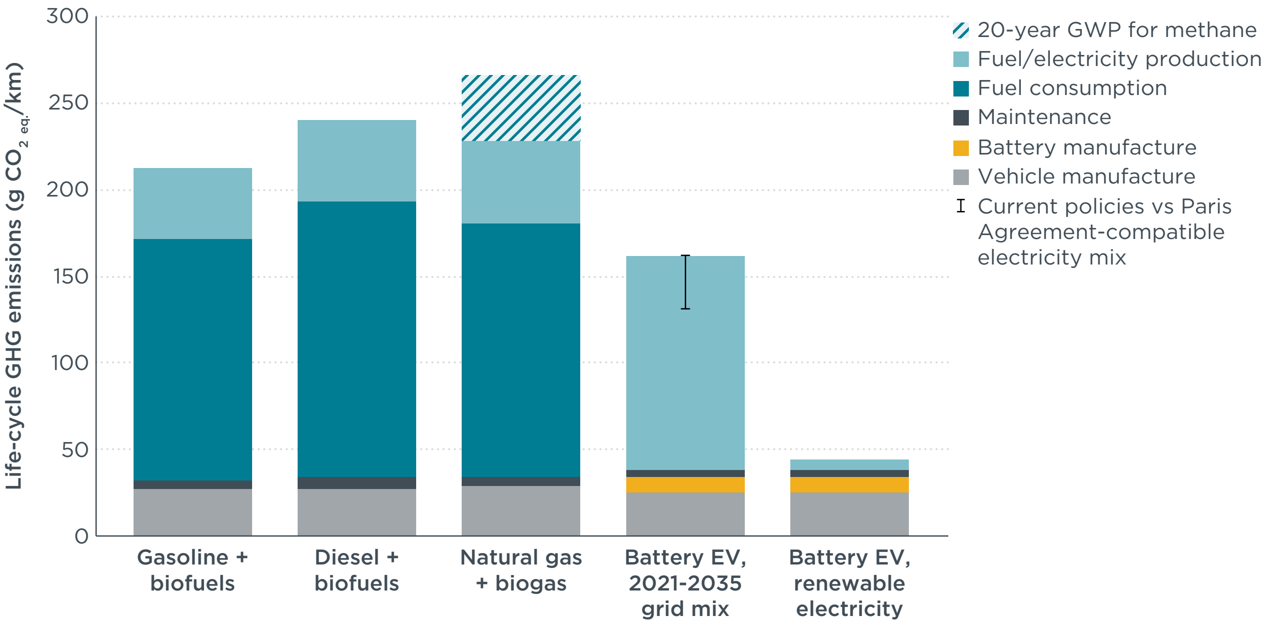

Figure 6.1. Life-cycle GHG emissions of hatchback segment gasoline, diesel, and CNG ICEVs and BEVs registered in India in 2021.

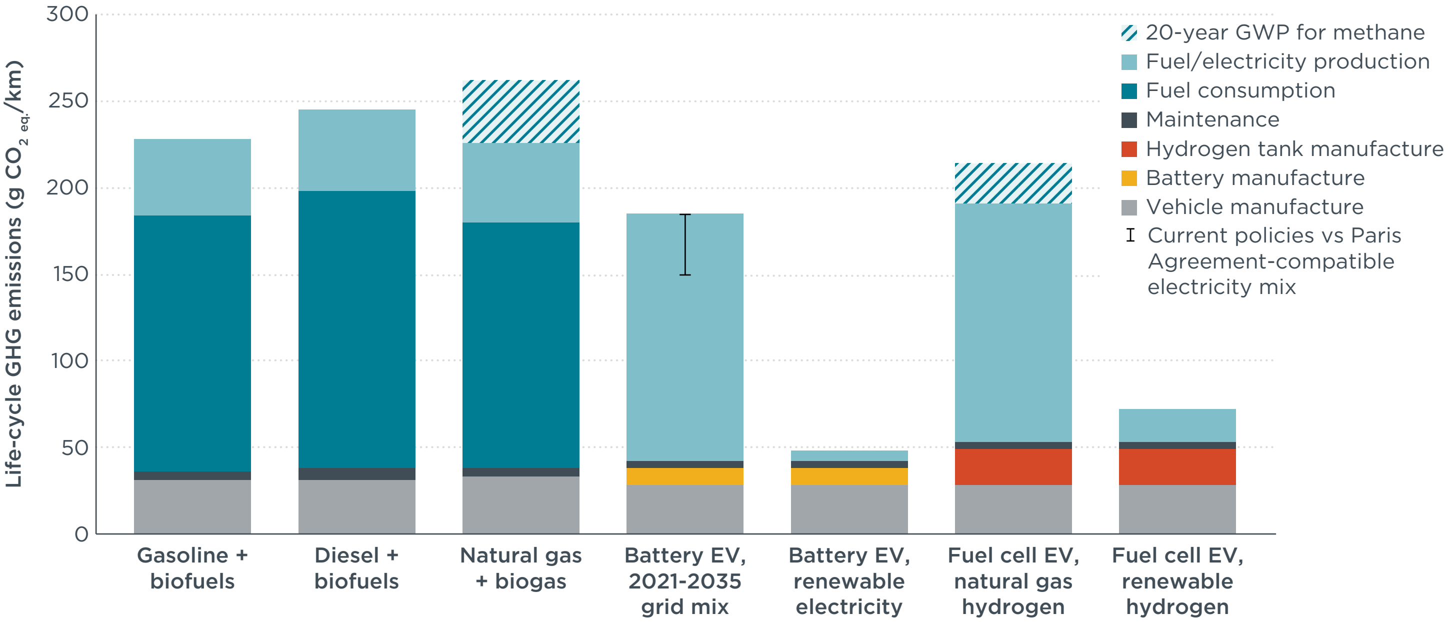

Figure 6.2. Life-cycle GHG emissions of sedan segment gasoline, diesel, and CNG ICEVs, BEVs, and FCEVs registered in India in 2021.

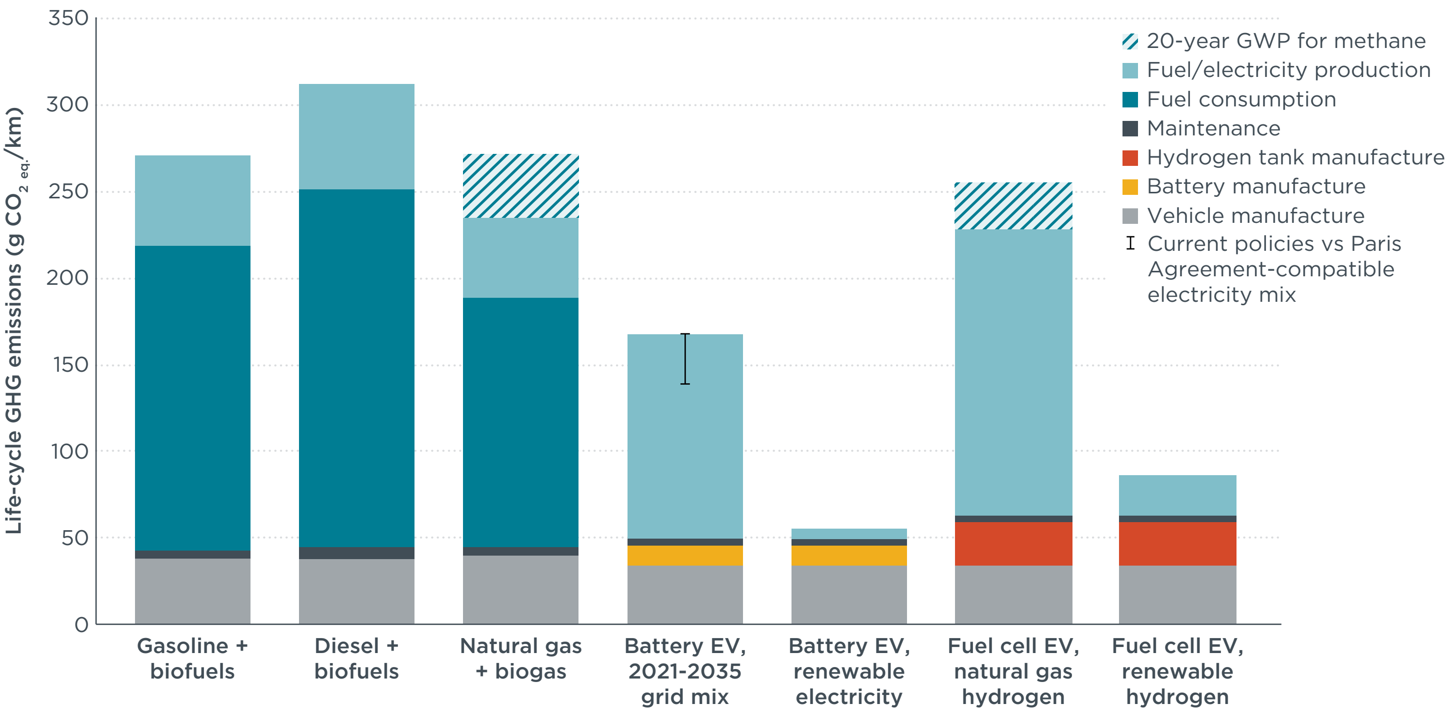

Figure 6.3. Life-cycle GHG emissions of SUV segment gasoline, diesel, and CNG ICEVs, BEVs, and FCEVs registered in India in 2021.

Diesel cars correspond to higher life-cycle GHG emissions than gasoline cars

The life-cycle GHG emissions of average gasoline cars correspond to 213 g $CO_{2\ eq.}$/km for hatchback, 228 g $CO_{2\ eq.}$/km for sedan, and 272 g $CO_{2\ eq.}$/km for SUV segment cars. For diesel cars, these levels are 13%–16% higher, at 241 g $CO_{2\ eq.}$/km for hatchback, 245 g $CO_{2\ eq.}$/km for sedan, and 317 g $CO_{2\ eq.}$/km for SUV segment cars. This is because the 20% higher carbon intensity per liter of diesel compared to gasoline (**Table A.9**) is only partly compensated by the 3%–12% lower fuel consumption in India (**Table A.8**). For comparison, the fuel consumption of diesel cars in Europe is 9%–18% lower than for comparable gasoline cars.

CNG cars show similar emissions as gasoline cars, but could be worse with methane slip

CNG cars do not provide a GHG emissions benefit over gasoline cars. With 229 g $CO_{2\,eq.}$/km for hatchback, 226 g $CO_{2\,eq.}$/km for sedan, and 237 g $CO_{2\,eq.}$/km for SUV segment CNG cars, the life-cycle GHG emissions are higher than for gasoline cars in the hatchback segment, similar in the sedan segment, and lower in the SUV segment.

When considering the near-term, 20-year GWP of the methane emissions of natural gas production and from the methane slip emissions from the vehicles, the GHG emissions of CNG cars are even higher, at 266 g $CO_{2\,eq.}$/km, 263 g $CO_{2\,eq.}$/km, and 274 g $CO_{2\,eq.}$/km.

These numbers are based on the assumption that methane slip emissions from CNG vehicles in India are as low as was found for Euro 6 cars in Europe, at 60 mg CH_4/km (Prussi et al., 2020; Vojtíšek-Lom et al., 2018; Hagos & Ahlgren, 2018). In contrast, the methane slip from CNG cars in China is as high as 2% (Pan et al., 2020). With a fuel consumption of 5 kg per 100 km, this corresponds to about 1,000 mg CH_4/km and thus an additional 30 g $CO_{2\,eq.}$/km for the 100-GWP and 85 g $CO_{2\,eq.}$/km for the 20-year GWP. If the methane slip emissions of CNG cars in India were to be as high as in China, CNG cars would be the powertrain type with the highest GHG emissions.

Future increase in biofuel shares would have little influence on the GHG emissions of 2021 cars

For cars registered in 2021, the considered increase in the ethanol and biogenic diesel shares reduces life-cycle GHG emissions by only 3% for gasoline cars and 1% for diesel cars. For CNG cars, the biomethane share decreases the emissions by only 1%. This is due to two factors. First, as displayed in **Tables A.17 to A.19** in the Appendix, the production of biofuels can correspond to significant GHG emissions, as well. In the case of molasses-based ethanol, the production and indirect land use change GHG emissions are considered with 41 g $CO_{2\,eq.}$/MJ (El Takriti et al., 2017), which is about half as high as for the production and combustion emissions of fossil gasoline of 93 g $CO_{2\,eq.}$/MJ. Second, although the GHG emissions corresponding to ethanol made from energy crops and residues are very low, they are considered to be producible in similar volumes as molasses-based ethanol only by 2030. Similarly, industry needs time to ramp up to produce diesel from used cooking oil and wastes, and sewage-based biomethane (Pavlenko & Searle, 2019).

Depending on the scenario, BEVs correspond to 19%–49% lower emissions than gasoline cars

Depending on whether the electricity mix is considered to develop according to the IEA's STEPS or SDS, the life-cycle GHG emissions of currently registered BEVs in India are at 131–162 g $CO_{2\,eq.}$/km for the hatchback segment, 150–185 g $CO_{2\,eq.}$/km for the sedan segment, and 140–169 g $CO_{2\,eq.}$/km for the SUV segment. Under the STEPS, the life-cycle GHG emissions of BEVs in India are 19%–38% lower than for average gasoline cars, and under the SDS, they are 38%–49% lower.

Solely renewable electricity-powered in BEVs correspond to even lower life-cycle GHG emissions of 44–56 g $CO_{2\,eq.}$/km, which is 82%–83% lower than for gasoline cars.

FCEVs are only low carbon when using CCS or renewable electricity-based hydrogen

Driving on natural gas-based (grey) hydrogen corresponds to life-cycle GHG emissions of 191 g $CO_{2\,eq.}$/km and 230 g $CO_{2\,eq.}$/km for sedan and SUV segment FCEVs. These levels are 16% lower than the emissions of comparable gasoline cars. When considering the higher 20-year GWP of the upstream methane leakage emissions, the GHG emission levels increase to 214 g $CO_{2\,eq.}$/km and 257 g $CO_{2\,eq.}$/km, which is only 6% lower than for gasoline cars.

When combining the production of (blue) hydrogen from natural gas with CCS, the emission levels would decrease to 95–114 g $CO_{2\ eq.}$/km for the 100-year GWP and 118–141 g $CO_{2\ eq.}$/km for the 20-year GWP, which is 58% and 48% lower than for gasoline cars. When using only renewable electricity-based (green) hydrogen, the life-cycle GHG emissions of sedan and SUV segment FCEVs are estimated at 73–84 g $CO_{2\ eq.}$/km, which is 68% lower than for gasoline cars.

6.2 2030 PASSENGER CARS

Data and assumptions

For passenger cars registered in FY 2022–23, India's corporate average fuel consumption standards require fleet average MIDC test CO_2 emissions of about 109.4 g CO_2/km, which is about 11% lower than the average MIDC CO_2 emissions in FY 2019–20 levels (Deo, 2021). In parallel, with its commitment to the EV30@30 campaign of the Clean Energy Ministerial forum, the Government of India targets at a 30% electric vehicle share of new car registrations in 2030 (Gode et al., 2021). With this share, even if the FY 2022–23 fuel consumption standards were to be significantly strengthened, the fuel efficiency of the remaining fleet of new gasoline, diesel, and CNG cars would not need to improve compared to today's levels. Therefore, as for Europe, the fuel consumption of average combustion engine cars in 2030 is considered to remain the same as for 2021 cars. Further, in the absence of policies that reduce the electricity and hydrogen consumption of BEVs and FCEVs, these are also considered to remain at current levels.

Regarding battery capacity, 2030 BEVs in India are assumed to be similar to the 2030 models in Europe and China. Therefore, battery capacity is twice as high as for the current BEV models in India. Apart from that, changes in the life-cycle GHG emissions of 2030 cars are mostly determined by the increased biofuel shares in the gasoline, diesel, and natural gas blend, as well as by the continuously reduced share of coal power in the electricity mix.

LCA results and discussion

Figures 6.4 to 6.6 show the estimated life-cycle GHG emissions of hatchback, sedan, and SUV segment cars projected to be registered in 2030.

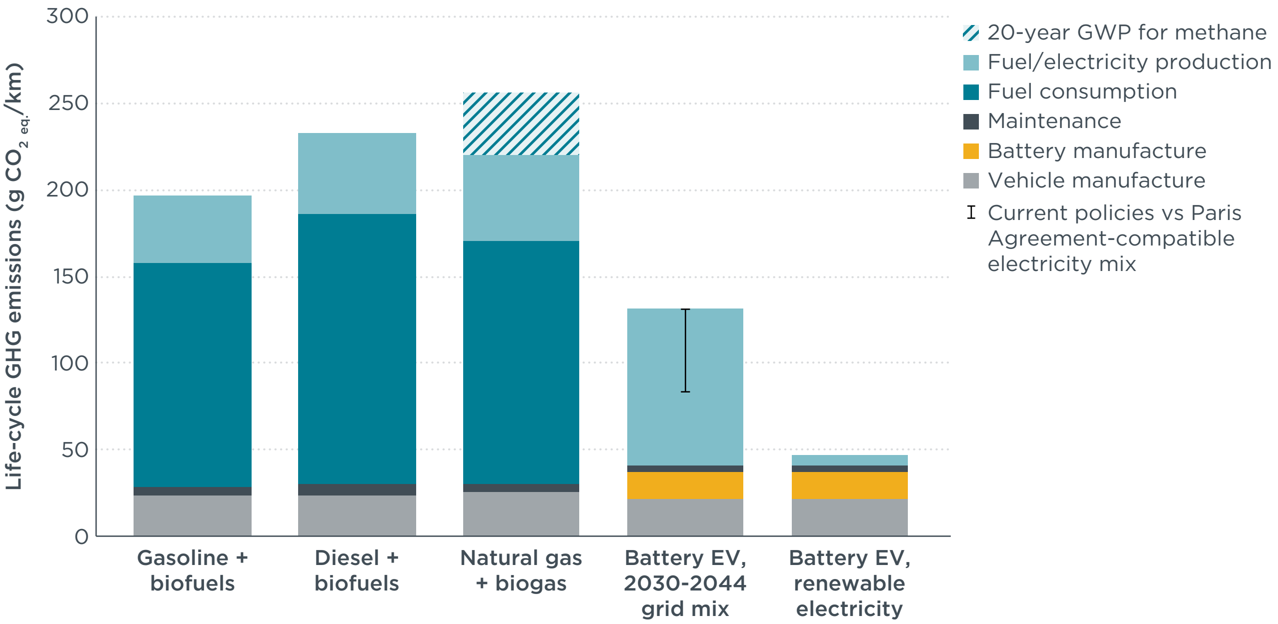

Figure 6.4. Life-cycle GHG emissions of hatchback segment gasoline, diesel, and CNG ICEVs, and BEVs projected to be registered in India in 2030.

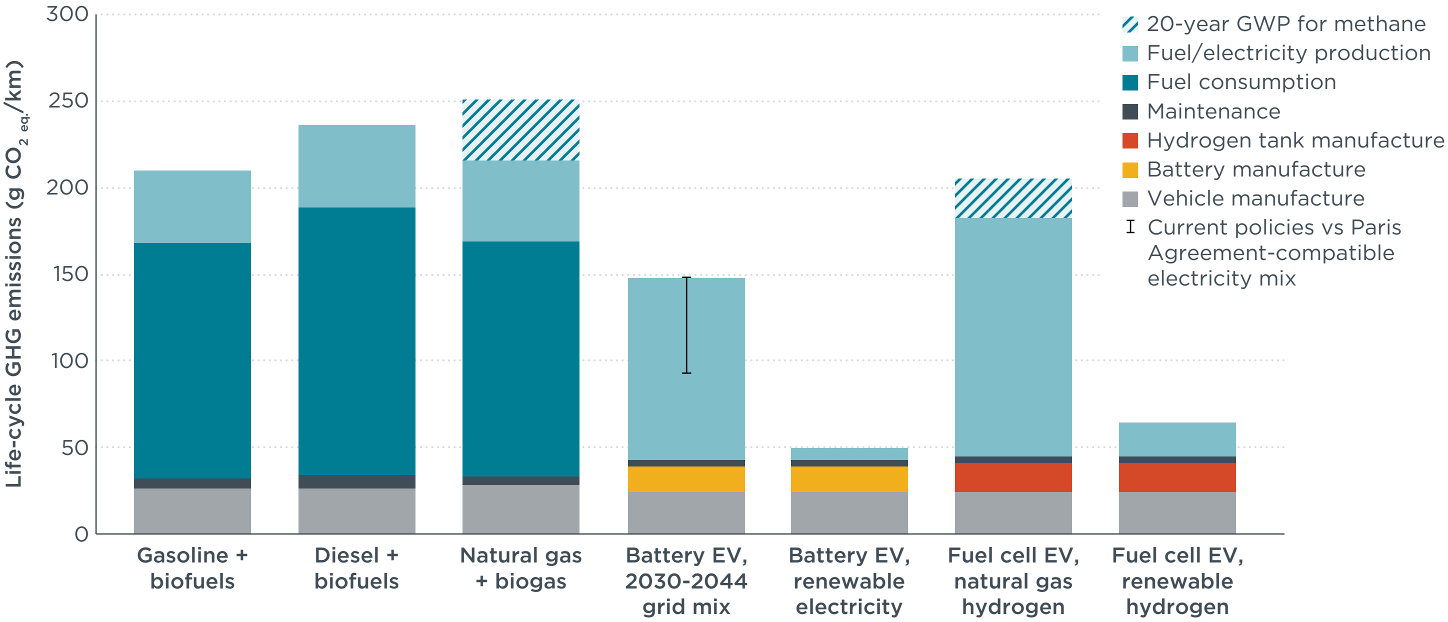

Figure 6.5. Life-cycle GHG emissions of sedan segment gasoline, diesel, and CNG ICEVs, BEVs, and FCEVs projected to be registered in India in 2030.

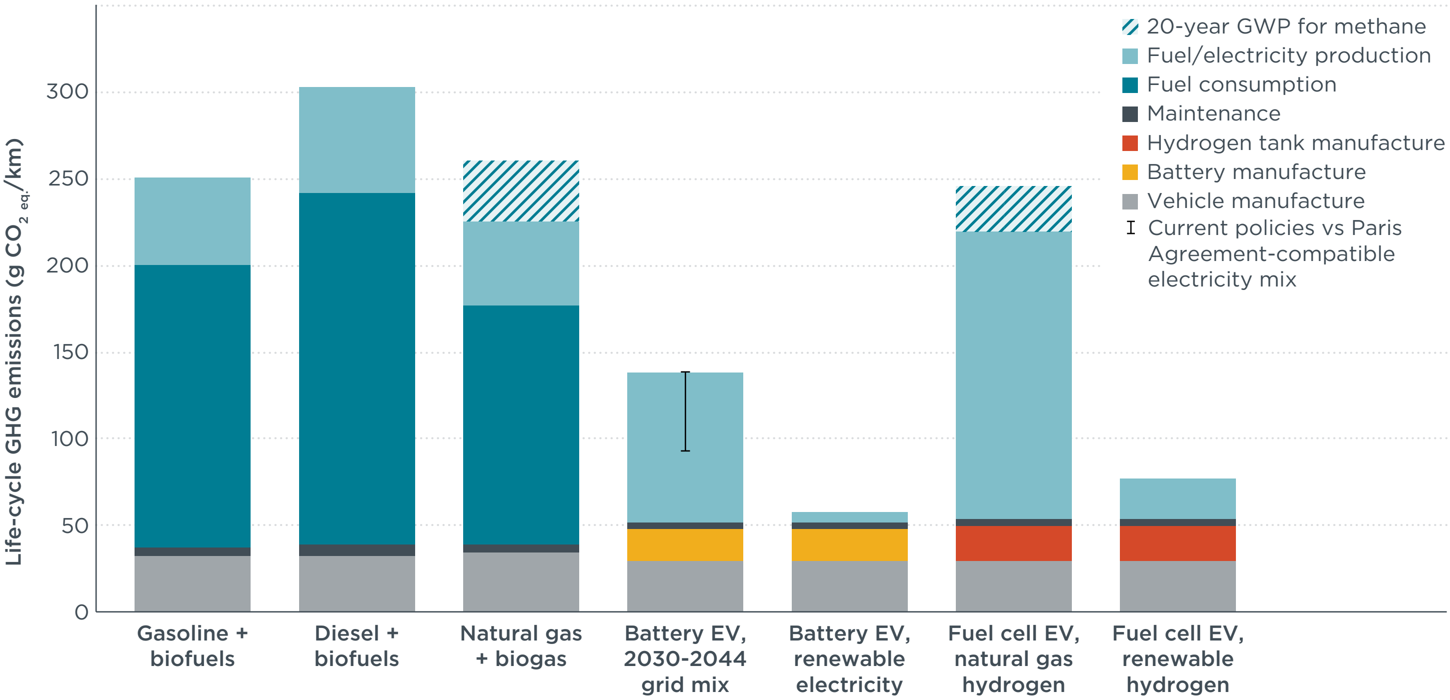

Figure 6.6. Life-cycle GHG emissions of SUV segment gasoline, diesel, and CNG ICEVs, BEVs, and FCEVs projected to be registered in India in 2030.

For 2030 gasoline cars, the high advanced ethanol shares reduce the GHG emissions by 9%

During the lifetime of 2030 gasoline cars, the ethanol share is considered to increase from about 11% in 2030 to 20% in 2040 (**Table A.17**, based on Pavlenko & Searle, 2019). Since most of this ethanol is considered to be produced from residues and energy crops, it significantly decreases the estimated life-cycle GHG emissions of gasoline cars. They are at 197 g $CO_{2\ eq.}$/km for hatchback, 210 g $CO_{2\ eq.}$/km for sedan, and 251 g $CO_{2\ eq.}$/km for SUV segment cars. While for 2021 gasoline cars, the considered increase in the advanced ethanol share results in only 3% lower life-cycle GHG emissions, the additional volumes of advanced biofuels reduce the GHG emissions of 2030 cars by 9% compared to driving with the current gasoline blend.

For diesel cars, the 4%–5% share of waste-based biodiesel in 2030 (**Table A.18**) results in 3% lower life-cycle GHG emissions than for the current diesel blend. For hatchback, sedan, and SUV segment diesel cars, they are at 233 g $CO_{2\ eq.}$/km, 236 g $CO_{2\ eq.}$/km and 303 g $CO_{2\ eq.}$/km, respectively. Thereby, the life-cycle GHG emissions of 2030 diesel cars remain at 12%–21% higher levels than for gasoline cars.

With a biomethane share of 5% in 2030 and 10% in 2040 (**Table A.19**), the life-cycle GHG emissions of CNG cars registered in 2030 are 4% lower than for CNG cars registered in 2021, at 219 g $CO_{2\ eq.}$/km for the hatchback segment, 216 g $CO_{2\ eq.}$/km for the sedan segment, and 226 g $CO_{2\ eq.}$/km for SUVs. When considering the 20-year GWP, they are at 251–261 g $CO_{2\ eq.}$/km.

BEVs correspond to 30%–63% lower life-cycle GHG emissions than gasoline cars

For BEVs, the continuous decrease of the share of coal power in India's electricity mix results in significantly lower life-cycle GHG emissions. Although partly offset by the larger battery capacity, they are at 83–131 g $CO_{2\ eq.}$/km for hatchback, 93–148 g $CO_{2\ eq.}$/km for sedan, and 93–139 g $CO_{2\ eq.}$/km for SUV segment cars. Thereby, the life-cycle GHG emissions of BEVs registered in 2030 are 30%–45% or 56%–63% lower than for gasoline cars, depending on whether the STEPS or the SDS electricity mix projections are considered.

GHG emissions for the individual hydrogen pathways remain similar to those of 2021 cars

The decreasing emissions from the production of the hydrogen tank and the rest of the vehicle only slightly reduce the life-cycle GHG emissions of 2030 FCEVs compared to the 2021 cars. For grey hydrogen FCEVs in 2030, they are at 183–220 g $CO_{2\ eq.}$/km for the 100-year GWP and 205–247 g $CO_{2\ eq.}$/km for the 20-year GWP. Compared to gasoline vehicles in 2030, which are increasingly powered by advanced biofuels, the relative GHG emissions reduction of driving on grey hydrogen instead of gasoline is diminished further, to 12% for the 100-year GWP and 2% for the 20-year GWP.

For FCEVs running on blue hydrogen, life-cycle GHG emissions are estimated at 87–104 g $CO_{2\ eq.}$/km for the 100-year GWP and 109–131 g $CO_{2\ eq.}$/km for the 20-year GWP. For green hydrogen, the life-cycle GHG emissions are at 64–77 g $CO_{2\ eq.}$/km.

6.3 SUMMARY AND CONCLUSIONS

The life-cycle GHG emissions of BEVs registered in India today are significantly lower than for gasoline, diesel, or CNG cars. With a continuous decarbonization of the average power grid, their relative GHG emissions benefit increases quickly, even when considering an optimistic increase of the share of advanced biofuels in the gasoline, diesel, and natural gas blends. FCEVs, in contrast, only show a minor GHG emission benefit compared to combustion engine cars when powered by the currently dominant natural gas-based hydrogen. In order to correspond to low GHG emissions, FCEVs need to be powered by renewable electricity-based hydrogen or by hydrogen produced from natural gas combined with CCS.

BEVs

Even with the coal-intensive electricity mix in India, the life-cycle GHG emissions of 2021 cars are 19%–49% lower than for average gasoline cars. This large range reflects the gap between the STEPS and what the SDS considers to be required to limit global warming to below 2°C, as is the goal of the Paris Agreement. For BEVs projected to be registered in 2030, the life-cycle GHG emissions are 30%–63% lower than of the emissions of respective gasoline cars.

FCEVs

While the life-cycle GHG emissions of FCEVs using natural gas-based hydrogen are only slightly lower than the emissions of average gasoline cars, CCS (blue hydrogen) and renewable electricity-based hydrogen allow a deep reduction of GHG emissions. Due to a potential leakage of CO_2 from the storage sides, however, CCS requires careful regulation and monitoring (Zhou, 2020).

Driving FCEVs solely on renewable electricity-based hydrogen corresponds to the pathway with one of the lowest life-cycle carbon intensities, second only to driving BEVs on renewable energies. Still, as discussed in the Europe part, the energy demand of driving on electricity-based hydrogen is about three times higher than for directly using the electricity for driving BEVs. While renewable electricity capacities remain limited, the availability of renewable electricity for this less efficient technology is a concern. Also, to avoid diverting the renewable electricity from an existing use, it must be ensured that the renewable energy used for hydrogen production is delivered by new, additional power plants.

Biofuels

Limiting biofuel policy support to low-carbon energy crop-, residues-, and waste-based biofuel feedstocks can significantly contribute to a reduction of the life-cycle GHG emissions of combustion engine cars. However, as discussed by Pavlenko and Searle (2019), it could require decades to ramp up the necessary biofuel production capacities. For gasoline cars, it is shown that when increasing the ethanol share from the current 5% to 20% in 2040 only with additional volumes of energy crop and residues-based ethanol, results in 8% lower life-cycle GHG emissions for the cars projected to be registered in 2030. Over the lifetime of gasoline cars registered today, however, the life-cycle GHG emissions are only reduced by 3%. For diesel and CNG cars, the future shares of waste-based biodiesel and sewage-based biomethane result in an improvement of the life-cycle GHG emissions of 1% for cars registered this year and 3%–4% for the cars expected to be registered in 2030.

In comparison to the decarbonization of the power grid, which results in 20%–40% lower GHG emissions over the lifetime of BEVs registered in 2030 compared to BEVs registered today, the high increase in advanced biofuel shares considered in the India has relatively little impact on the life-cycle GHG emissions of combustion engine passenger cars. Also, advanced biofuels are also considered to be an important decarbonization strategy for heavy-duty road transport, shipping (Zhou et al., 2020), and aviation (Pavlenko, 2021; O'Malley et al., 2021). The future demand for advanced biofuels from these segments may further limit the volumes available for passenger cars.

CNG cars

The life-cycle GHG emissions of CNG cars in India are found to be as high as for comparable gasoline cars. For the small hatchback segment, however, where CNG cars are most popular, the GHG emissions of average CNG cars are higher than gasoline cars. Additionally, when considering the near-term, 20-year GWP of the upstream methane emissions, the life-cycle GHG emissions of CNG cars significantly exceed the levels of average gasoline cars.

These numbers consider the low methane slip emissions that were found for Euro 6 cars in Europe. When considering the methane slip reported for CNG cars in China, however, the life-cycle GHG emissions of CNG cars registered in 2021 would correspond to 20%–25% higher values than for gasoline cars. When considering the 20-year GWP, they would be 62%–67% higher than for gasoline cars.

7 GLOBAL SUMMARY AND IMPLICATIONS FOR POLICY

7.1 GLOBAL TRENDS

Despite certain regional differences, the relative GHG emissions performance of the different powertrains follows the same trend in all investigated regions. Only BEVs and FCEVs driving on renewable electricity-based hydrogen allow for a deep reduction in life-cycle GHG emissions compared to the currently dominant gasoline cars. While PHEVs and natural gas hydrogen-powered FCEVs show a minor reduction of GHG emissions over gasoline cars, average diesel and CNG cars do not.

In Figures 7.1 and 7.2, these trends are summarized for global typical medium-size passenger cars registered in 2021 and projected to be registered in 2030, respectively.

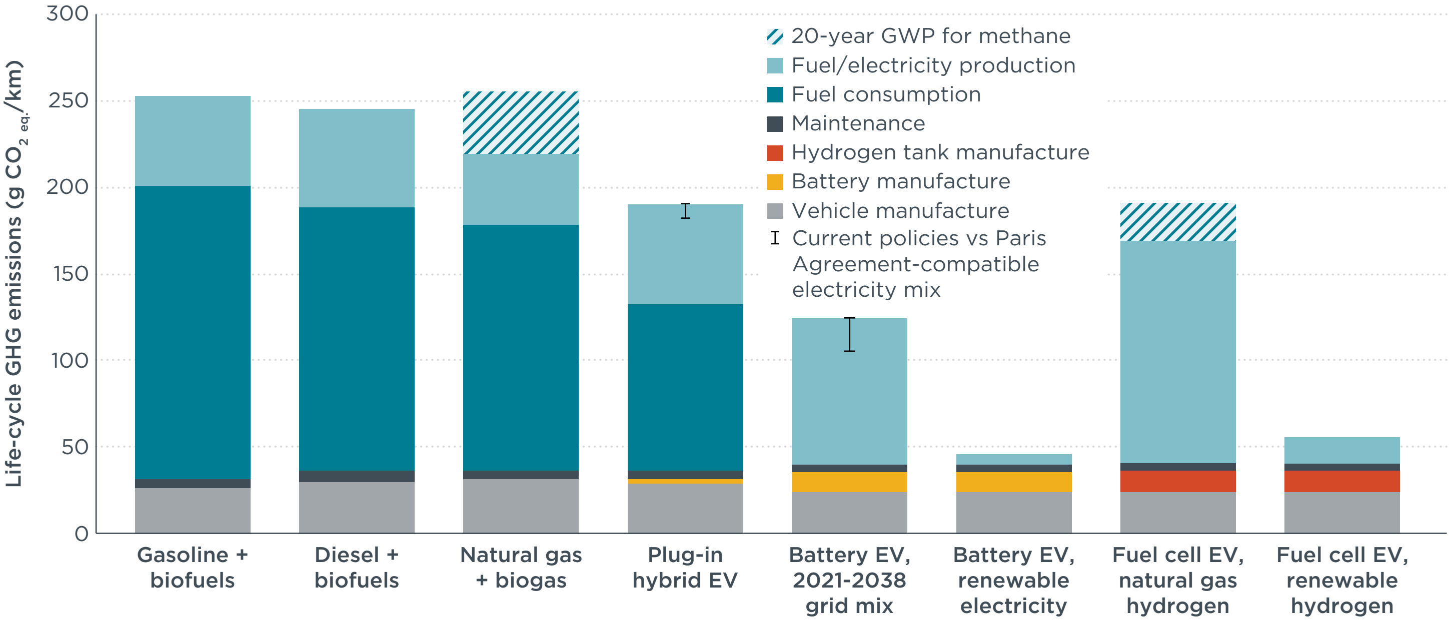

Figure 7.1. Life-cycle GHG emissions of average medium-size gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs registered in China, Europe, India, and the United States, in 2021.

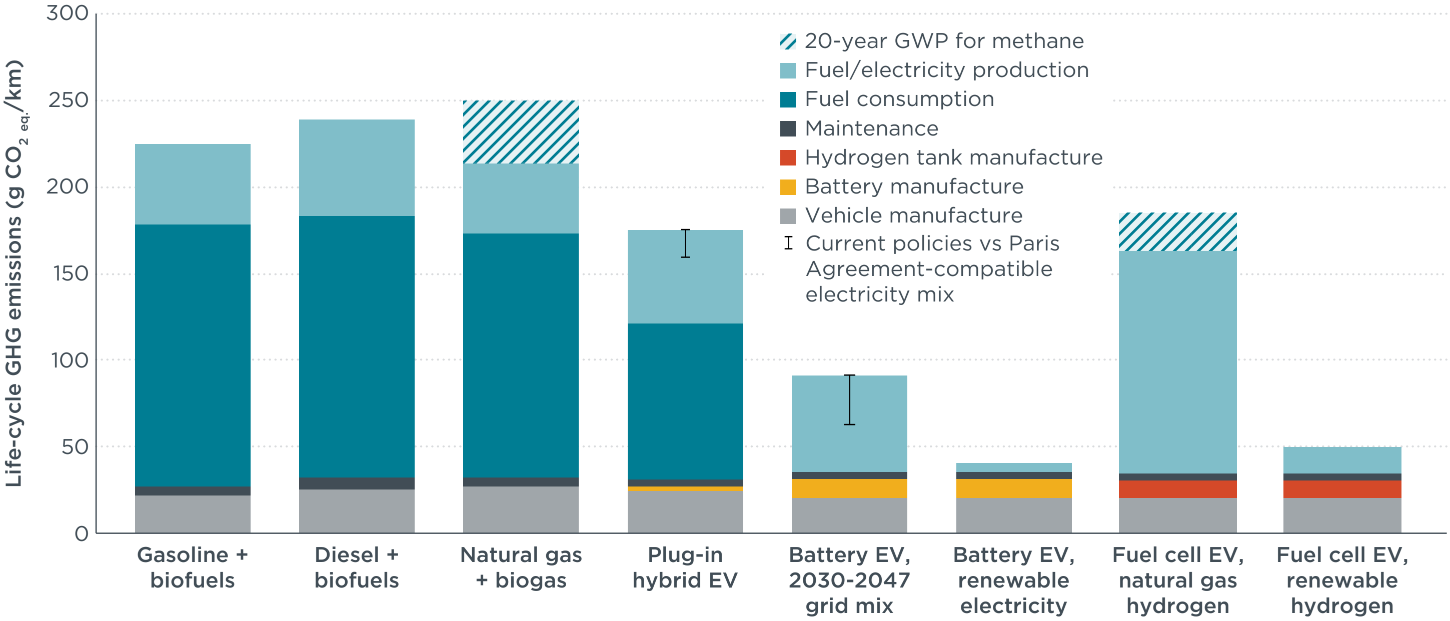

Figure 7.2. Life-cycle GHG emissions of average medium-size gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs projected to be registered in China, Europe, India, and the United States in 2030.

The figures present the life-cycle GHG emissions of average lower medium segment vehicles in Europe, passenger cars in the United States, A segment cars in China, and sedan segment cars in India, weighted by the 2019 total car registrations in the respective regions. These four regions account for about 70% of the global new car sales in 2019 (European Automobile Manufacturers Association, 2020).

Gasoline cars

Gasoline cars (including HEVs) are the dominant powertrain type for passenger cars. Their life-cycle GHG emissions can be influenced by fuel efficiency or CO_2 standards and the biofuels blend. As found in this study, the stated policy fuel efficiency or CO_2 standards for cars registered in 2030 would not significantly reduce the life-cycle GHG emissions of average gasoline cars in Europe, the United States, or India. Even the ambitious fuel efficiency target in China would reduce these emissions by only about 19%. Similarly, as discussed further at the end of this section, the expected changes in biofuel blends have a low-to-negligible influence on the life-cycle GHG emissions of current and future gasoline cars.

HEVs

As a more fuel-efficient variant of gasoline cars, this study considers HEVs as part of the average fleet of gasoline cars. This means that the considered improvement of the fuel efficiency of future average gasoline cars may already include a higher share of HEVs. As assessed for average HEVs in Europe, their real-world fuel consumption is about 25% lower than for conventional gasoline cars, and their life-cycle GHG emissions are about 20% lower.

Diesel cars

In Europe and India, the life-cycle GHG emissions of diesel cars are similar or even higher than for gasoline cars. In addition, the upstream GHG emissions of the production of diesel, especially when containing high land use change biofuels such as palm oil-based biodiesel, are typically found to be higher than for the average gasoline blend.

CNG cars

When driving on the average mix of natural gas and biomethane, CNG cars correspond to 11%–19% lower life-cycle GHG emissions than gasoline cars in Europe. In India, though, the life-cycle GHG emissions of CNG cars are found to be similar to those of gasoline cars, or even higher. When considering the 20-year GWP of upstream methane emissions from natural gas production, the climate impact of CNG cars exceeds the levels of gasoline cars in both regions.

PHEVs

The life-cycle GHG emissions of PHEVs differs between the United States, Europe, and China. While in the United States, PHEVs show about 35%–46% lower life-cycle GHG emissions than gasoline cars, they correspond to a reduction of 25%–31% in Europe and only 8%–14% in China. Compared to the much lower life-cycle GHG emissions of BEVs in these regions, the GHG emission reduction potential of PHEVs is only moderate, also for PHEVs in the United States.

BEVs

Across all investigated regions and passenger car segments, BEVs show significantly lower life-cycle GHG emissions than average gasoline cars. As presented for medium size vehicles in Figure 7.3, 2021 BEVs in Europe and the United States correspond to 63%–69% and 57%–68% of the life-cycle GHG emissions of average gasoline vehicles. For cars projected to be registered in 2030, the life-cycle GHG emissions of BEVs in these regions are 71%–77% and 61%–76% lower than for the respective average gasoline cars.

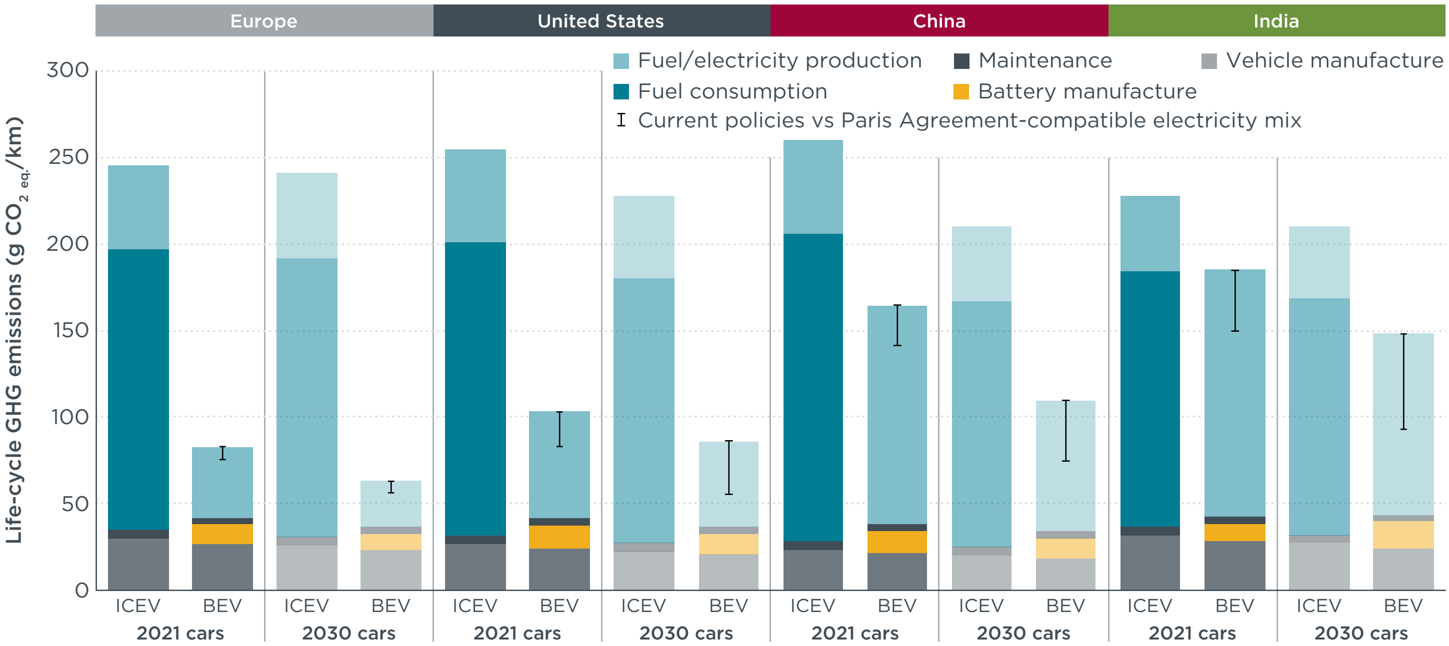

Figure 7.3. Life-cycle GHG emissions of average medium-size gasoline ICEVs and BEVs. The error bars indicate the difference between the development of the electricity mix according to the IEA's Stated Policy Scenario or Sustainable Development Scenario.

Due to the currently high share of coal power in China and India, the life-cycle GHG emissions of BEVs in these regions are higher than in Europe or the United States. Nevertheless, also here, BEVs correspond to significantly lower GHG emissions than gasoline, diesel, or CNG cars. Already over the lifetime of cars registered in China and India in 2021, BEVs show 34%–54% and 19%–49% lower life-cycle GHG emissions than gasoline cars. For the cars expected to be registered in 2030, BEVs correspond to 46%–67% and 30%–63% lower life-cycle GHG emissions than for the respective future gasoline cars.

The wide range of the life-cycle GHG emissions of BEVs is reflective of the differences between the electricity mix projections in the IEA's Stated Policy Scenario (STEPS) and what the Sustainable Development Scenario (SDS) considers to be necessary in order to limit global warming to below 2 °C (IEA, 2020). Given the commitments under the Paris Agreement, future policies are expected to continuously approach the SDS projections.

For cars registered in 2040 or 2050, the life-cycle GHG emissions of BEVs are expected to approach the levels of solely renewable electricity-powered BEVs, which are about 80% lower than for today's gasoline vehicles.

FCEVs

While BEVs registered in 2021 offer a large GHG emissions benefit when powered by the average electricity grid—even for the currently coal-intensive grids in China and India—FCEVs only correspond to low GHG emissions when powered by relatively higher shares of renewable electricity-based (green) hydrogen or CCS (blue) hydrogen. As presented for medium-size FCEVs in Figure 7.4, driving on coal-based (black) hydrogen corresponds to the same level of GHG emissions compared to gasoline cars, and natural gas-based (grey) hydrogen shows 24%–33% lower values.

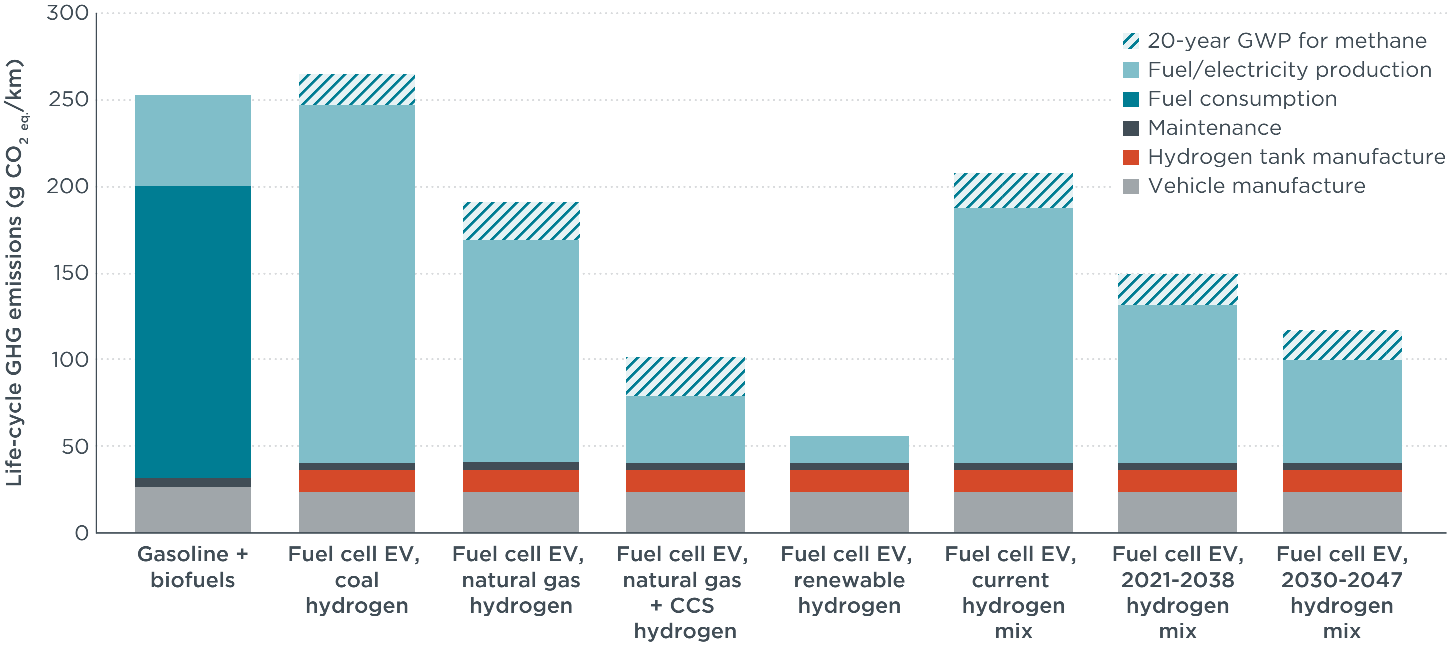

Figure 7.4. Life-cycle GHG emissions of global typical medium-size FCEVs powered by coal-, natural gas-, CCS natural gas-, or renewable electricity-based hydrogen, by the current mix of these pathways and by the expected lifetime average mix for cars registered in Europe, the United States, China, and India in 2021 and in 2030, compared to global typical gasoline cars registered in 2021.

In addition to the individual hydrogen pathways, the figure shows the GHG emissions of driving with the current average hydrogen mix of the four regions and with the lifetime average hydrogen mix of FCEVs registered in 2021 and in 2030.[12] These assumptions of the future hydrogen mixes show that FCEVs could correspond to similarly low life-cycle GHG emissions as do average electricity-powered BEVs.

As discussed in the Europe part of the analysis, the energy demand of driving on renewable electricity-based hydrogen is three times higher than for using that electricity directly in BEVs. While renewable capacities remain limited, the availability of renewable electricity for less efficient technologies is a concern (Ueckerdt et al., 2021). Also, to avoid diverting renewable electricity from an existing use, it must be ensured that the renewable energy used by FCEVs is delivered by new, additional power plants.

E-fuels

For driving on e-fuels, the required amount of renewable electricity is six times as high as it is for driving BEVs, and this demand is reflected in high e-fuels production costs. As exemplified for Europe, the production costs of e-fuels are estimated to be about €3 per liter diesel equivalent higher than for fossil fuels, also in the 2030–2050 time frame (Searle & Christensen, 2018). The policy support needed to price e-fuels competitively given this gap in production costs is currently not foreseeable. Nevertheless, even if it were, the producible volumes of e-fuels in 2030, 2040, and

12 While for Europe, the United States and India, the current blend of hydrogen pathways is almost entirely based on natural gas-based hydrogen (IEA, 2019), the current mix China is considered with 73% coal and 27% natural gas hydrogen. In addition, byproduct hydrogen is a relevant pathway in the hydrogen mix in China (China EV100, 2020). As it is not scalable and thus might only play a role in the mid-term, it is not considered in this study. By 2030, the hydrogen mix in Europe is optimistically assumed to develop into a 50:50 mix of blue and green hydrogen, the future hydrogen mix in the United States could contain equal shares of grey, blue, and green hydrogen, the mix in China could be a 50:50 mix of grey and blue hydrogen and the mix in India could be a 50:50 mix of grey and green hydrogen. For the global typical values displayed in Figure 7.4, the life-cycle carbon intensities of the regional mixes are weighted by the 2019 total car registrations in the four regions.

2050 are estimated to correspond to about 0.3%, 1.7%, and 4.0% of the fuel currently consumed in road transport in the European Union. For combustion engine cars registered in 2030, these shares would reduce the lifetime average carbon intensity of the fuel blend by less than 2%.

When considering that a proportion of these limited volumes of e-fuels would be used in sectors of transport that are more difficult to decarbonize, especially in aviation (Pavlenko, 2021; O'Malley et al., 2021) the volumes of e-fuels available for passenger cars is even lower.

Biofuels

Especially for food-based biofuels such as corn ethanol or rapeseed oil-based biodiesel, indirect land use change emissions significantly increase the climate impact of their production. As depicted in Figure 7.5, for the most relevant ethanol and biodiesel feedstocks in the gasoline and diesel blends of the four regions of this study,[13] the life-cycle carbon intensity of biofuels can be similar or even higher than for the production and combustion of fossil gasoline or diesel.

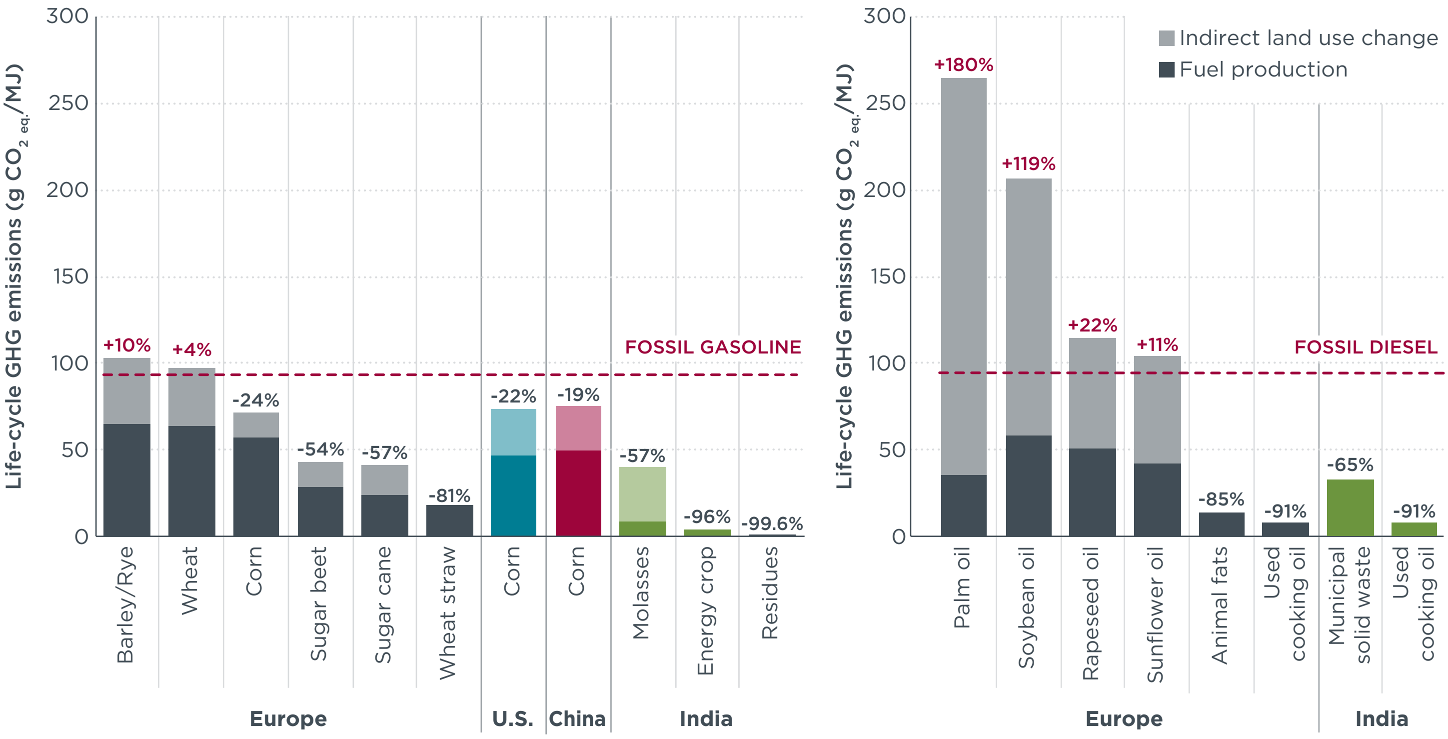

Figure 7.5. Production and indirect land use change emissions of the most relevant a) ethanol and b) biodiesel pathways considered in the gasoline and diesel blend in Europe, the United States, China, and India, compared to the production and combustion emissions of fossil gasoline and diesel.

Because they are largely based on food-based biofuel feedstocks, the ethanol blends in Europe, the United States, and China reduce the life-cycle GHG emissions of gasoline cars in these regions by 2% or less compared to driving only on fossil gasoline. For biodiesel and HVO, the mostly food-based feedstocks used in Europe are even found to even increase the life-cycle GHG emissions of diesel cars.

For more significant reductions of the carbon intensity of the gasoline and diesel blend in these regions, food-based biofuels could be replaced by advanced, waste- and

13 See **Tables A.11 to A.18** in the Appendix.

residues-based feedstocks. As found for in earlier studies (Searle & Malins, 2015; Pavlenko et al., 2019; Pavlenko & Searle, 2020), however, the available volumes of waste and residues are limited, the production costs can be high, and the production capacities would need time to scale up.

India's stated biofuels policy foresees an ambitious increase of advanced biofuels. Due to the time required for scaling up their production, however, the life-cycle GHG emissions over the lifetime of gasoline, diesel, and CNG cars registered in 2021 are only slightly affected. For cars registered in 2030, meanwhile, the GHG emissions benefit provided by the higher shares of advanced biofuels is more substantial. However, when compared to the deep reduction in GHG emissions that the BEVs provide in India in the same time frame, these improvements are minor.

In addition, similar to e-fuels, the use of advanced, low-carbon biofuels in other sectors of transportation, like aviation (Pavlenko, 2021; O'Malley et al., 2021) and shipping (Zhou et al., 2020), are expected to reduce the volumes available for passenger cars.

7.2 POLICY IMPLICATIONS

This assessment of the life-cycle GHG emissions of passenger cars shows that to align with the best efforts to limit global warming to below 2 °C, the global passenger car stock needs to become almost entirely electric by 2050. This has numerous policy implications globally:

Vehicle fleet regulations

The sale of new combustion engine vehicles should be phased out by 2030–2035.

BEVs and FCEVs powered by low-carbon hydrogen show the lowest life-cycle GHG emissions already for cars registered today and they are the only powertrain types than can provide deep reductions of the GHG emissions of passenger cars if they are largely powered by renewables. Due to vehicle lifetimes of at least 15–18 years, the sale of new combustion engine passenger cars, including HEVs and PHEVs, needs to be phased out globally by 2030–2035.

Future combustion engine vehicles, including HEVs, are found to allow only minor reductions in life-cycle GHG emissions, with a maximum of 20% for replacing conventional gasoline cars by HEVs or a maximum of 9% for the high shares of advanced biofuels considered in the lifetime average fuel mix of gasoline cars registered in India in 2030. Future PHEVs can correspond to larger, but still not large enough, reductions. With a higher electric range than today's models, PHEVs registered in the United States, Europe, and China in 2030 are expected to show 48%–56%, 31%–33%, and 18%–23% lower life-cycle GHG emissions compared to gasoline vehicles registered in these regions in 2021. Even when all of the electricity they consume is from renewables, the GHG emissions benefit from 2030 cars compared to 2021 cars would increase to only 60%, 36%, and 29% in the respective regions.

Fuel efficiency regulations support the transition to BEVs and FCEVs.

Fuel efficiency and CO_2 emission standards that prioritize zero tailpipe emission vehicles and ZEV share targets help to continuously decrease the share of combustion engine vehicles in new sales and thereby prepare for their phase out. In the meantime, fuel efficiency and CO_2 standards can help to reduce the emissions of the last generation of combustion engine cars. This transition can be supported by fiscal policies, charging infrastructure deployment, zero-emission zones, and further policies.

Incentivizing a higher electric drive share can improve the emissions impact of PHEVs.

As discussed in detail by Plötz et al. (2020), the currently low electric drive share of PHEVs in average real-world usage results in two kind of policy implications. For one, the accounting of PHEVs as part of fleet-wide fuel efficiency and CO_2 emission standards needs to be adjusted to better reflect their real-world usage and climate impact. Second, a higher share of electric driving should be incentivized by linking any fiscal benefits to the actual real-world electric drive share. The latter can be achieved, for example, by using data collected from on-board fuel consumption meters or during regular technical inspections, by incentivizing the sale of PHEV models with a higher electric range and a high ratio of electric motor to combustion engine power, or by supporting public, home, and workplace charging infrastructure.

Fuel and electricity supply

The need is for parallel decarbonization of the road transport and power sectors.

Given the life-cycle GHG benefits that BEVs registered in 2021 already show, it is important that a global transition to BEVs occur alongside the decarbonization of the power sector, and without any delay in expectation of power sector improvements. Vehicle lifetimes of 15–18 years further reinforce this, as the benefits of a decarbonized power sector in 2050 can only be captured in full by the transport sector if the BEV transition is complete for new sales by the early 2030s.

The use of hydrogen in road transport should focus on green hydrogen.

This study shows that incentivizing FCEVs without supporting the production and use of low-GHG hydrogen will not necessarily contribute to transport decarbonization. Green hydrogen production policies can include production subsidies, investment grants, tax reductions, mandates on fuel suppliers to supply green hydrogen, mandates on hydrogen suppliers to supply a share of green hydrogen, inclusion of green hydrogen in larger renewable fuel or fuel GHG reduction policies, or any combination of these measures.

Only truly low-carbon biofuels should be incentivized.

This study shows that biofuels and biogas can deliver a limited amount of GHG reductions to the transport sector, provided that only sustainable, low-carbon biofuels and biogas are used. Policies should focus support on the fuel pathways that offer the greatest GHG reductions and have substantial potential to scale up production, such as cellulosic biofuels. Policy support for truly low-carbon biofuels and biogas can include per liter subsidies, tax reductions, investment grants, and mandates on fuel suppliers to supply a share (or set amount of GHG reductions from) advanced, low-carbon fuels.

Vehicle production

Recycling can reduce the carbon footprint of vehicle production and support resource availability.

The life-cycle GHG emissions of the manufacture of batteries, the hydrogen system, and for the rest of the vehicle can be reduced through policies that require sustainable sourcing of materials, regulate the energy and emissions intensity of production, promote circular design, and set high collection and recycling targets.[14] In the case of batteries, high recycling targets also reduce the raw material dependency (Slowik et al., 2020).

14 As exemplified for NMC622-graphite batteries in **Section A.3** in the Appendix, stringent and element-specific recycling targets could reduce GHG emissions by 16%–25%, depending on the applied recycling process (Argonne National Laboratory, 2020).

REFERENCES

Agora Verkehrswende. (2019a). *Klimabilanz von Elektroautos—Einflussfaktoren und Verbesserungspotenzial*. Retrieved from https://www.agora-verkehrswende.de/veroeffentlichungen/klimabilanz-von-elektroautos/

Agora Verkehrswende. (2019b). *Klimabilanz von strombasierten Antrieben und Kraftstoffen*. Retrieved from https://www.agora-verkehrswende.de/veroeffentlichungen/?tx_agorathemen_themenliste%5Bprodukt%5D=1691&cHash=934f46d26c224a4d69df999d55d94129

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

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., … Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*, *361*(6398), 186–188. https://doi.org/10.1126/science.aar7204

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

Baldino, C., O'Malley, J., Searle, S., Zhou, Y., & Christensen, A. (2020). *Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/hydrogen-heating-UK-dec2020

Bansal, G., & Bandivadekar, A. (2013). *Overview of India's vehicle emissions control program*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/indias-vehicle-emissions-control-program

Bäumer, M., Hautzinger, H., Pfeiffer, M., Stock, W., Lenz, B., Kuhnimhof, T., & Köhler, K. (2017). *Fahrleistungserhebung 2014 – Inländerfahrleistung*. Retrieved from Bundesanstalt für Straßenwesen, https://bast.opus.hbz-nrw.de/frontdoor/index/index/docId/1774

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. (2020). *Altfahrzeug-Verwertungsquoten in Deutschland im Jahr 2018*. Retrieved from https://www.bmu.de/download/jahresberichte-ueber-die-altfahrzeug-verwertungsquoten-in-deutschland/

Buysse, C., Miller, J., Díaz, S., Sen, A., & Braun, C. (2021). *The role of the European Union's vehicle CO_2 standards in achieving the European Green Deal*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/eu-vehicle-standards-green-deal-mar21

California Air Resources Board. (2017). *California's Advanced Clean Cars midterm review: Appendix A: Analysis of zero emission vehicle regulation compliance scenarios*. Retrieved from https://www.arb.ca.gov/msprog/acc/acc-mtr.htm

China Automotive Technology and Research Center. (2017). *Report on the development of China energy-saving and new energy vehicle*. Retrieved from http://www.catarc.info/attached/file/20180313/20180313161921_3486.pdf

China EV100. (2020). *China Hydrogen Energy Development Roadmap 1.0: How to realize a green, efficient and economical hydrogen energy supply system?*

China Society of Automotive Engineers. (2020). *Energy-saving and new energy vehicle technology roadmap 2.0*. Retrieved from http://www.sae-china.org/news/society/202010/3957.html

China State Council. (2020). *New-Energy Vehicle Industrial Development Plan 2021–2035*. http://www.gov.cn/zhengce/content/2020-11/02/content_5556716.htm

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

Ciez, R. E., & Whitacre, J. F. (2019). Examining different recycling processes for lithium-ion batteries. *Nature Sustainability*, *2*(2), 148–156. https://doi.org/10.1038/s41893-019-0222-5

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

Dai, Q., Kelly, J. C., Gaines, L., & Wang, M. (2019). Life cycle analysis of lithium-ion batteries for automotive applications. *Batteries, 5*(2), 48. https://doi.org/10.3390/batteries5020048

Deo, A. (2021). *Fuel consumption from new passenger cars in India: Manufacturers' performance in fiscal year 2019–20*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/fuel-consumption-pv-india-apr2021

Díaz, S., Mock, P., Bernard, Y., Bieker, G., Pniewska, I., Ragon, P.-L., Rodríguez, F., Tietge, U., & Wappelhorst, S. (2020). *European vehicle market statistics 2020/21*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/european-vehicle-market-statistics-202021

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*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/way-real-world-co2-values-european-passenger-car-market-its-first-year-after

Dun, C., Horton, G., Kollamthodi, S. (2015). *Improvements to the definition of lifetime mileage of light duty vehicles*. Ricardo-AEA report for the European Commission. Retrieved from https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_mileage_improvement_en.pdf

El Takriti, S., Searle, S., & Pavlenko, N. (2017). *Indirect greenhouse gas emissions of molasses ethanol in the European Union*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/indirect-greenhouse-gas-emissions-molasses-ethanol-european-union

Emilsson, E., & Dahllöf, L. (2019). *Lithium-ion vehicle battery production*. Retrieved from the IVL Swedish Environmental Research Institute, https://www.ivl.se/download/18.14d7b12e16e3c5c36271070/1574923989017/C444.pdf

Emisia. (2013). *Transport data collection supporting the quantitative analysis of measures relating to transport and climate change (TRACCS)*. Emisia, INFRAS, and IVL. https://traccs.emisia.com/index.php

European Automobile Manufacturers Association. (2019). *Vehicles in use—Europe 2019*. Retrieved from https://www.acea.be/uploads/publications/ACEA_Report_Vehicles_in_use-Europe_2019.pdf

European Automobile Manufacturers Association. (2020). *The automotive industry pocket guide 2020/2021*. Retrieved from https://www.acea.be/uploads/publications/ACEA_Pocket_Guide_2020-2021.pdf

European Parliament, & Council of the European Union. (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources*. http://data.europa.eu/eli/dir/2018/2001/oj

European Parliament, & Council of the European Union. (2019). *Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (Text with EEA relevance.)* (No. 32019R0631; pp. 13–53). http://data.europa.eu/eli/reg/2019/631/oj/eng

Few, S., Schmidt, O., Offer, G. J., Brandon, N., Nelson, J., & Gambhir, A. (2018). Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: An analysis informed by expert elicitations. *Energy Policy*, *114*, 578–590. https://doi.org/10.1016/j.enpol.2017.12.033

Fisch und Fischl GmbH. (2021, May). *Spritmonitor.de*. https://www.spritmonitor.de/

Gode, P., Bieker, G., & Bandivadekar, A. (2021). *Battery capacity needed to power electric vehicles in India from 2020 to 2035*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/battery-capacity-ev-india-feb2021

Hagos, D. A., & Ahlgren, E. O. (2018). Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – Perspectives on gas in transport in Denmark. *Transportation Research Part D: Transport and Environment*, *65*, 14–35. https://doi.org/10.1016/j.trd.2018.07.018

Hall, D., & Lutsey, N. (2018). *Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/EV-battery-manufacturing-emissions

Hao, H., Wang, H., Ouyang, M., & Cheng, F. (2011). Vehicle survival patterns in China. *Science China Technological Sciences*, *54*(3), 625–629. https://doi.org/10.1007/s11431-010-4256-1

Harlow, J. E., Ma, X., Li, J., Logan, E., Liu, Y., Zhang, N., … 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

Heinemann, C., Kasten, P., Bauknecht, D., Bracker, J., Bürger, V., Emele, L., Hesse, T., … Timpe, C. (2019). *Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland*. Retrieved from Öko-Institut e.V., https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf

Hill, N., Amaral, S., Morgan-Price, S., Nokes, T., Bates, J., Helms, H. … Bauen, A. (2020). *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*. Ricardo-AEA, ifeu, and E4tech report for the European Commission. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1

Hmiel, B., Petrenko, V. V., Dyonisius, M. N., Buizert, C., Smith, A. M., Place, P. F., … Dlugokencky, E. (2020). Preindustrial $^{14}CH_4$ indicates greater anthropogenic fossil CH_4 emissions. *Nature*, *578*(7795), 409–412. https://doi.org/10.1038/s41586-020-1991-8

Huo, H., Zhang, Q., He, K., Yao, Z., & Wang, M. (2012). Vehicle-use intensity in China: Current status and future trend. *Energy Policy*, *43*, 6–16. https://doi.org/10.1016/j.enpol.2011.09.019

Huss, A., & Weingerl, P.. (2020). *JEC Tank-to-wheel report v5: Passenger cars*. Publications Office of the European Union. Retrieved from https://ec.europa.eu/jrc/en/publication/jec-tank-wheel-report-v5-passenger-cars

Intergovernmental Panel on Climate Change. (2013). *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York. Retrieved from https://www.ipcc.ch/report/ar5/wg1/

International Council on Clean Transportation. (2020). *Vision 2050: A strategy to decarbonize the global transport sector by mid-century*. Retrieved from https://theicct.org/publications/vision2050

International Energy Agency. (2021, May). *Electric power transmission and distribution losses*. Retrieved from https://data.worldbank.org/indicator/eg.elc.loss.zs

International Energy Agency. (2019). *The future of hydrogen*. Report for the G20. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

International Energy Agency. (2020). *World energy outlook 2020*. Retrieved from www.iea.org/weo

International Energy Agency. (2021). *India energy outlook 2021*. Retrieved from www.iea.org/reports/india-energy-outlook-2021

Isenstadt, A., & Lutsey, N. (2020). *Summary of the Trump Administration's fatally flawed U.S. light-duty vehicle efficiency standards*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/fatally-flawed-trump-NHTSA-analysis

Karuppannan Gopalraj, S., & Kärki, T. (2020). A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: Fibre recovery, properties and life-cycle analysis. *SN Applied Sciences*, *2*(3), 433. https://doi.org/10.1007/s42452-020-2195-4

Kelly, J. C., Dai, Q., & Wang, M. (2019). Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. *Mitigation and Adaptation Strategies for Global Change*, *25*, 371–396. https://doi.org/10.1007/s11027-019-09869-2

Kraftfahrt-Bundesamt. (2011). *Fahrzeugalter*. Retrieved from https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/Fachartikel/alter_20110415.pdf

Kurland, S. D. (2019). Energy use for GWh-scale lithium-ion battery production. *Environmental Research Communications*, *2*(1), 012001. https://doi.org/10.1088/2515-7620/ab5e1e

Liu, H., Man, H., Cui, H., Wang, Y., Deng, F., Wang, Y., ... He, K. (2017). An updated emission inventory of vehicular VOCs and IVOCs in China. *Atmospheric Chemistry and Physics*, *17*(20), 12709–12724. https://doi.org/10.5194/acp-17-12709-2017

Lu, S. (2006). *Vehicle survivability and travel mileage schedules* (Technical Report No. DOT HS 809 952). Retrieved from the National Highway Traffic Safety Administration, https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/809952

Malins, C., & Searle, S. (2019). *A critique of lifecycle emissions modeling in "The greenhouse gas benefits of corn ethanol—Assessing recent evidence."* Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/critique-lifecycle-emissions-modeling-ghg-ethanol

Mantzos, L., Wiesenthal, T., Neuwahl, F. and Rozsai, M. (2019). *The POTEnCIA central scenario: An EU energy outlook to 2050*. Publications Office of the European Union. Retrieved from https://publications.jrc.ec.europa.eu/repository/handle/JRC118353

Mehlhart, G., Kosinska, I., Baron, Y., & Hermann, A. (2018a). *Assessment of the implementation of Directive 2000/53/EU on end-of-life vehicles (the ELV Directive) with emphasis on the end of life vehicles of unknown whereabouts*. Öko-Institut report for the European Commission. Retrieved from https://data.europa.eu/doi/10.2779/446025

Mehlhart, G., Möck, A., & Goldman, D. (2018b). *Effects on ELV waste management as a consequence of the decisions from the Stockholm Convention on decaBDE* (p. 104). Retrieved from Öko-Institut, https://www.oeko.de/fileadmin/oekodoc/ACEA-DecaBDE-final-report.pdf

Ministry of Industry and Information Technology. (2015). *Made in China 2025 – Promoting Energy Saving and New Energy Vehicle Development*.

Mock, P. (2019). *CO_2 emission standards for passenger cars and light-commercial vehicles in the European Union*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/ldv-co2-stds-eu-2030-update-jan2019

Mock, P., & Díaz, S. (2021). *Pathways to decarbonization: The European passenger car market, 2021–2035*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/decarbonize-EU-PVs-may2021

Mock, P., Tietge, U., Wappelhorst, S., Bieker, G., & Dornoff, J. (2021). *Market monitor: European passenger car registrations, January–December 2020*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/market-monitor-eu-jan2021

Moomaw, W., P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, A. Verbruggen, (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. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/03/Annex-II-Methodology-1.pdf

Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1 „Klimaschutz im Verkehr". (2020). *Werkstattbericht alternative Kraftstoffe—Klimawirkungen und Wege zum Einsatz alternativer Kraftsstoffe*. Retrieved from https://www.plattform-zukunft-mobilitaet.de/2download/werkstattbericht-alternative-kraftstoffe-wege-zur-dekarbonisierung-schwerer-lkw-mit-fokus-der-elektrifizierung/

O'Malley, J., Pavlenko, N., & Searle, S. (2021). *Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/sustainable-aviation-fuel-feedstock-eu-mar2021

Pan, D., Tao, L., Sun, K., Golston, L. M., Miller, D. J., Zhu, T., … Zondlo, M. A. (2020). Methane emissions from natural gas vehicles in China. *Nature Communications*, *11*(1), 4588. https://doi.org/10.1038/s41467-020-18141-0

Pavlenko, N. (2021). *An assessment of the policy options for driving sustainable aviation fuels in the European Union*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/sustainable-aviation-fuel-policy-eu-apr2021

Pavlenko, N., & Searle, S. (2019). *The potential for advanced biofuels in India: Assessing the availability of feedstocks and deployable technologies*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/potential-advanced-biofuels-india-assessing-availability-feedstocks-and-deployable

Pavlenko, N., & Searle, S. (2020). *Assessing the potential advanced alternative fuel volumes in the Netherlands in 2030*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/alternative-fuel-netherlands-May2020

Pavlenko, N., Searle, S., & Baldino, C. (2019). *Assessing the potential advanced alternative fuel volumes in Germany in 2030*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/potential-advanced-fuel-volumes-germany

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), 939–945. https://doi.org/10.1038/s41560-017-0032-9

Philippot, M., Alvarez, G., Ayerbe, E., Van Mierlo, J., & Messagie, M. (2019). Eco-efficiency of a lithium-ion battery for electric vehicles: Influence of manufacturing country and commodity prices on GHG emissions and costs. *Batteries*, *5*(1), 23. https://doi.org/10.3390/batteries5010023

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*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/phev-real-world-usage-sept2020

Riemersma, I., & Mock, P. (2017). *Too low to be true? How to measure fuel consumption and CO_2 emissions of plug-in hybrid vehicles, today and in the future*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/too-low-be-true-how-measure-fuel-consumption-and-co2-emissions-plug-hybrid-vehicles

Romare, M., & Dahllöf, L. (2017). *The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries*. Retrieved from IVL Swedish Environmental Research Institute, https://www.ivl.se/english/ivl/publications/publications/the-life-cycle-energy-consumption-and-greenhouse-gas-emissions-from-lithium-ion-batteries.html

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

Searle, S., & Christensen, A. (2018). *Decarbonization potential of electrofuels in the European Union*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/decarbonization-potential-electrofuels-eu

Searle, S., & Malins, C. (2015). A reassessment of global bioenergy potential in 2050. *GCB Bioenergy*, *7*(2), 328–336. https://doi.org/10.1111/gcbb.12141

Slowik, P., Lutsey, N., & Hsu, C.-W. (2020). *How technology, recycling, and policy can mitigate supply risks to the long-term transition to zero-emission vehicles*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/mitigating-zev-supply-risks-dec2020

Suarez-Bertoa, R., & Astorga, C. (2018). Impact of cold temperature on Euro 6 passenger car emissions. *Environmental Pollution*, *234*, 318–329. https://doi.org/10.1016/j.envpol.2017.10.096

Suresh, P. (2016). *Environmental and economic assessment of transportation fuels from municipal solid waste* (Master's thesis). Retrieved from the Massachusetts Institute of Technology, https://dspace.mit.edu/bitstream/handle/1721.1/105567/963833797-MIT.pdf?sequence=1

Taszka, S., & Domergue, S. (2019). *Prime à la conversion des véhicules particuliers en 2018*. Retrieved from Ministère de la Transition écologique et solidaire, https://www.actu-environnement.com/media/pdf/news-34355-prime-vehicule-2018.pdf

Tietge, U., Díaz, S., Yang, Z., & Mock, P. (2017). *From laboratory to road international: A comparison of official and real-world fuel consumption and CO_2 values for passenger cars in Europe, the United States, China, and Japan*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/laboratory-road-intl

Transport & Environment. (2020). *How clean are electric cars? T&E's analysis of electric car lifecycle CO_2 emissions*. Retrieved from https://www.transportenvironment.org/sites/te/files/downloads/T%26E%E2%80%99s%20EV%20life%20cycle%20analysis%20LCA.pdf

Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer, G. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Climate Change*, *11*(5), 384–393. https://doi.org/10.1038/s41558-021-01032-7

United Nations Environment Programme. (2020). *Used vehicles and the environment*. Retrieved from https://wedocs.unep.org/handle/20.500.11822/34175

U.S. Department of Agriculture. (2020). *China biofuels annual*. Retrieved from https://www.fas.usda.gov/data/china-biofuels-annual-6

U.S. Department of Energy. (2021, May). *Alternative Fuels Data Center*. https://afdc.energy.gov/

U.S. Department of Transportation. (2017). *National Household Travel Survey*. Retrieved from https://nhts.ornl.gov

U.S. Department of Transportation. (2021, May). *Bureau of Transportation Statistics*, *National transportation statistics*. https://www.bts.gov/topics/national-transportation-statistics

U.S. Environmental Protection Agency. (2010). *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. (2021). *The 2020 EPA automotive trends report*. Retrieved from https://www.epa.gov/automotive-trends

U.S. Environmental Protection Agency, & U.S. Department of Energy. (2020). *Fuel economy guide model year 2019*. Retrieved from https://www.fueleconomy.gov/

U.S. Environmental Protection Agency, & U.S. Department of Energy. (2021, May). *MyMPG*. https://www.fueleconomy.gov/mpg/MPG.do

U.S. Environmental Protection Agency, & U.S. Department of Transportation. (2012). *Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards* (EPA-420-R-12-901). https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-model-year-2017-and-later-light-duty-vehicle

U.S. Environmental Protection Agency, & U.S. Department of Transportation. (2020). *The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks*. https://www.nhtsa.gov/corporate-average-fuel-economy/safe

Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., & Hamelinck, C. (2015). *The land use change impact of biofuels consumed in the EU*. Ecofys, IIASA and E4tech report for the European Commission. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf

Valverde, V., & Giechaskiel, B. (2020). Assessment of gaseous and particulate emissions of a Euro 6d-temp diesel vehicle driven >1300 km including six diesel particulate filter regenerations. *Atmosphere*, *11*(6), 645. https://doi.org/10.3390/atmos11060645

Vojtíšek-Lom, M., Beránek, V., Klír, V., Jindra, P., Pechout, M., & Voříšek, T. (2018). On-road and laboratory emissions of NO, NO_2, NH_3, N_2O and CH_4 from late-model EU light utility vehicles: Comparison of diesel and CNG. *Science of The Total Environment*, *616–617*, 774–784. https://doi.org/10.1016/j.scitotenv.2017.10.248

Wietschel, M., Kühnbach, M., & Rüdiger, D. (2019). *Die aktuelle Treibhausgasemissionsbilanz von Elektrofahrzeugen in Deutschland*. Retrieved from Fraunhofer Institute for Systems and Innovation Research ISI, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2019/WP02-2019_Treibhausgasemissionsbilanz_von_Fahrzeugen.pdf

Wietschel, M., Moll, C., Oberle, S., Timmerberg, S., Neuling, U., Kaltschmitt, M., & Ashley-Belbin, N. (2019). *Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw*. Retrieved from Fraunhofer Institute for Systems and Innovation Research ISI, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2019/klimabilanz-kosten-potenziale-antriebe-pkw-lkw.pdf

XiaoXiongYouHao. (2021, May). *XiaoXiongYouHao*. http://www.xiaoxiongyouhao.com/

Yang, Z., & Cui, H. (2020). *Technology roadmap and costs for fuel efficiency increase and CO_2 reduction from Chinese new passenger cars in 2030*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/china-costcurves-oct2020

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

Zhou, Y. (2020). Carbon capture and storage: A lot of eggs in a potentially leaky basket. *ICCT Staff Blog*. https://theicct.org/blog/staff/carbon-capture-storage-and-leakage

Zhou, Y., Pavlenko, N., Rutherford, D., Osipova, L., & Comer, B. (2020). *The potential of liquid biofuels in reducing ship emissions*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/marine-biofuels-sept2020

APPENDIX – DATA AND ASSUMPTIONS

A.1 VEHICLE CYCLE

Glider and powertrain

Table A.1 shows the GHG emissions used for the production and recycling[15] of the glider and powertrain (sans battery and hydrogen system) of lower medium cars in Europe. These values are based on a recent vehicle LCA study by Ricardo AEA, ifeu, and E4Tech (Hill et al., 2020) that focused on the European Union and United Kingdom.

Table A.1. GHG emissions of the production and recycling of the glider and powertrain of lower medium cars in the European Union and the United Kingdom and mass-based GHG emission factors derived from dividing these by the average mass of this segment in the European Union and the United Kingdom in 2019.

	t $CO_{2\ eq.}$	t $CO_{2\ eq.}/t_{vehicle}$
Gasoline ICEV	7.2	5.2
Diesel ICEV	7.2	5.2
CNG ICEV	7.6	5.5
PHEV (without battery)	7.9	5.7
BEV (without battery)	6.5	4.7
FCEV (without hydrogen system)	6.5	4.7

These values are comparable to other recent vehicle LCA studies (e.g., Hall & Lutsey, 2018; Agora Verkehrswende, 2019a; Wietschel et al., 2019a; Wietschel et al., 2019b; Transport & Environment, 2020), and the GREET model (Argonne National Laboratory, 2020). This is especially the case regarding the 10% lower GHG emissions of producing and recycling the glider and electric powertrain for BEVs and FCEVs compared to ICEVs and PHEVs. Dividing the Ricardo AEA values by the average mass in running order of lower medium segment cars in the European Union and United Kingdom in 2019 results in mass specific GHG emission factors. These are applied to the average vehicle mass of the respective segments.

In the European Union and the United Kingdom, the average mass of cars in the small, lower medium, and SUV segments registered in 2019 was 1,155 kg, 1,382 kg, and 1,537 kg, respectively (Díaz et al., 2020). In the United States, the average mass of passenger cars and SUVs[16] in 2019 was 1,593 kg and 1,935 kg, respectively (U.S. Environmental Protection Agency, 2021). For new cars in the A0, A, and SUV segments in China in 2019, the average mass was 1,112 kg, 1,281 kg, and 1,545 kg, respectively (data from China Automotive Technology and Research Center). In India, the average mass of hatchback, sedan, and SUV segment cars registered in FY 2019–20 was 876 kg, 998 kg, and 1,377 kg, respectively (data from Segment Y Automotive Intelligence). For 2030 cars in all four regions, the GHG emissions are assumed to decrease by 15% (Hill et al., 2020).

Hydrogen system

In recent vehicle LCA studies, the GHG emissions of the production of the hydrogen system, which contains a hydrogen tank and a fuel cell, correspond to about 5 t $CO_{2\ eq.}$ (Hill et al., 2020; Wietschel et al., 2019b; Agora Verkehrswende, 2019b) while they

15 There are two different approaches for considering the GHG emissions impact of recycling in an LCA, and both are subject to change over time. One is the cut-off approach, which considers the GHG emissions benefit of using recycled material for the production of the vehicles at one point in time, and the other is the avoided burden approach, which considers the GHG emissions credit of later recycling of parts of the vehicles at the end of life. The Ricardo AEA study used a dynamic, time-sensitive hybrid of the cut-off and avoided burden approaches.

16 Including SUVs from the regulatory classes of cars and trucks.

amount to 3.4-4.2 t $CO_{2\ eq.}$ in the GREET model (Argonne National Laboratory, 2020). These emissions mostly correspond the energy-intensive production of carbon fiber reinforced plastic for the high-pressure hydrogen tank. Using the numbers from the GREET model, this study considers 3.4 t $CO_{2\ eq.}$ for the hydrogen system of medium-size cars (Toyota Mirai, 5 kg hydrogen tank) and 4.2 t $CO_{2\ eq.}$ for SUVs (Hyundai Nexo, 6.3 kg hydrogen tank). For 2030 cars, the capacity of the hydrogen tank is assumed to remain the same, while the GHG emissions of the hydrogen tank and fuel cell manufacturing are considered to be reduced by 20%.

Maintenance

Depending on the powertrain type and segment, GHG emissions of vehicle maintenance during use phase are estimated to be 4–13 g $CO_{2\ eq.}$/km in recent LCA studies (Agora Verkehrswende, 2019a; Hill et al., 2020). Because BEVs and FCEVs use fewer consumables, they have lower maintenance GHG emissions; diesel cars, in contrast, consume urea in the exhaust aftertreatment and thus show higher maintenance emissions. This study assumes maintenance GHG emissions of 5 g $CO_{2\ eq.}$/km for gasoline and CNG powered ICEVs and PHEVs, 7 g $CO_{2\ eq.}$/km for diesel ICEVs, and 4 g $CO_{2\ eq.}$/km for BEVs and FCEVs.

Lifetime mileage

Europe

Cars registered in Europe are considered to be used for an average lifetime of 18 years. This is based on the average age of end-of-life vehicles in several countries: Germany in 2014–2016, which was 17–18 years (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020); 19 years in France in 2018 (Taszka & Domergue, 2019); and 20 years in Portugal and Poland in 2015 (Mehlhart et al., 2018b). It is also based on an average vehicle age of 16–17 years in Greece, Romania, Estonia, and Lithuania in 2018 (European Automobile Manufacturers Association, 2019). As these numbers correspond to cars that were registered about two decades ago, and vehicle lifetime has been observed to increase every year (European Automobile Manufacturers Association, 2019), assuming a lifetime of 18 years for cars registered in 2021 and 2030 is considered a conservative estimate.

Lower vehicle lifetimes used in other vehicle LCA studies might refer to the average age of cars that are deregistered in a certain country, for example 13 years in Germany in 2005–2009 (Kraftfahrt-Bundesamt, 2011) or 14 years in the United Kingdom in 2012–2013 (Dun et al., 2015). Especially for countries that export large numbers of second-hand cars, such as Germany (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020) and other European countries (Mehlhart et al., 2018a; United Nations Environment Programme, 2020), these cars continue to be used in other countries. Therefore, the numbers of 13–14 years do not cover the full vehicle lifetime.

The average annual mileage of small, lower medium, and upper medium segment cars in Germany in 2011 was found to be similar to the annual mileage in these segments in the average of all EU member states and the United Kingdom that same year (Emisia, 2013). Therefore, German mobility survey data is considered to be representative for the region. In 2014, the average annual mileage of small, lower medium, and SUV segment cars in Germany was 11,000 km/a, 13,500 km/a, and 15,000 km/a, respectively (Bäumer et al., 2017). With an average useful vehicle lifetime of 18 years, the lifetime mileage corresponds to 198,000 km for small, 243,000 km for lower medium, and 270,000 km for SUV segment cars.

From the German mobility survey data, it was further deduced that the annual mileage of passenger cars decreases by about 5% per year. Thereby, the annual mileage of a car in the 18th year, for instance, is only 42% of the annual mileage in the first year.

United States

The 15–16 year average lifetime often associated with passenger cars and light trucks in the United States is based on survival rate data from 2003 (Lu, 2006) and thus corresponds to vehicles that were registered before 1990. This is more than 30 years ago and there is no recent survival rate data available. Considering that the average age of light-duty vehicles in the United States has continuously increased, from 8.4 years in 1995 to 11.8 years in 2019 (U.S. Department of Transportation, 2021), the vehicle lifetime of cars registered today and projected to be registered in 2030 is considered to be higher than it was for pre-1990 cars. This study thus assumes an average lifetime of 18 years.

This study estimates the average lifetime mileage with the accumulated annual mileage per vehicle age over the first 18 years of usage. With annual mileage per vehicle age data from the 2017 National Household Travel Survey (U.S. Department of Transportation, 2017), the average lifetime mileages of passenger cars and SUVs were estimated to 314,000 km and 337,000 km. From the 2017 survey, it was further deduced that the annual mileage decreases linearly in the first 18 years. For both passenger cars and SUVs, the annual mileage is assumed to decrease linearly, by about 500 km/a per year.

China

The useful vehicle lifetime of passenger cars registered in China from the late 1990s to early 2000s was found to be about 15 years (Hao et al., 2011; China Automotive Technology and Research Center, 2017). For cars registered in 2021 and projected to be registered in 2030, it is expected to be significantly higher, in part because vehicle retirement after 15 years that was formerly mandatory was lifted in 2013. In a conservative estimate, however, this study assumes an average useful vehicle life of 15 years.

While the average annual mileage of private and commercial light-duty passenger vehicles varies between provinces, the national average is about 19,000 km/a (China Automotive Technology and Research Center, 2017; Liu et al., 2017; Huo et al., 2012). The study considers this fleet-wide average for A segment cars and SUVs. As passenger cars from small vehicle segments usually have a lower annual mileage, a 10% lower value is assumed for A0 segment cars. This results in a lifetime mileage of 256,500 km for A0 segment cars and 285,000 km for A segment cars and SUVs.

During the 15 years of vehicle usage, the annual mileage is assumed to decrease by 5% each year.

India

Based on ICCT's India Emissions Model (Bansal & Bandivadekar, 2013), an average vehicle lifetime of 15 years and lifetime mileages of 165,000 km for hatchback and sedan segment cars and 188,000 km for SUV segment cars are assumed. The annual mileage is further assumed to decrease by 3% per year.

A.2 FUEL CYCLE

Fuel and electricity consumption

Europe

The average real-world fuel consumption of new gasoline, diesel, and CNG cars in Europe in Table A.2 is derived from the segment-specific average NEDC fuel consumption of new cars registered the European Union and the United Kingdom in 2019 (Díaz et al., 2020) and a consumer-reported real-world to NEDC deviation of +37% for conventional gasoline and CNG cars, +50% for hybrid electric vehicles (HEVs), and +44% for diesel cars (Dornoff et al., 2020).

Table A.2. Average real-world fuel and electricity consumption values for small, lower medium, and SUV segment cars registered in the European Union and the United Kingdom in 2019.

fuel (L or kg)and electricity (kWh) consumption per 100 km	Small	Lower medium	SUV
Gasoline ICEV	6.5 L	7.1 L	7.9 L
Gasoline HEV	—	5.4 L	6.3 L
Diesel ICEV	5.4 L	5.9 L	7.2 L
CNG ICEV	4.5 kg	5.0 kg	5.1 kg
PHEV	—	4.1 L + 12.1 kWh	4.0 L + 14.8 kWh
BEV	19.9 kWh	20.6 kWh	21.9 kWh
FCEV	—	1.0 kg	1.2 kg

The fuel and electricity consumption of PHEVs in the lower medium and SUV segments is based on the BMW 225xe (2019 variant, 8.8 kWh battery capacity, 165 kW engine power) and the Mitsubishi Outlander PHEV (2018 variant, 13.8 kWh, 165 kW). With market shares of 60% and 37%, respectively, these two most popular models correspond to a large part of the PHEVs registered in the lower medium and SUV segment in the European Union and the United Kingdom in 2019 (Díaz et al., 2020). According to the average user-reported fuel consumption data on the German website Spritmonitor.de (Fisch und Fischl GmbH, 2021), 4.1 L/100 km for the BMW 225xe (2019, 165 kW) and 4.0 L/100 km for the Mitsubishi Outlander PHEV (2018, 165 kW) are considered as real-world values. For both models, these values are two times higher than the NEDC fuel consumption values of 1.9 L/100 km and 1.8 L/100 km. For the electricity consumption of these two PHEVs, data from the ADAC Ecotest (Allgemeiner Deutscher Automobil-Club, 2021) is used. The test provides fuel and electricity consumption values for the charge-depleting (CD) and charge-sustaining (CS) mode separately (Table A.3) and includes charging losses. With these and the user-reported fuel consumption of 4.1 L/100 km for the BMW 225xe and 4.0 L/100 km the Mitsubishi Outlander, average CD mode drive shares of 69% and 63% are calculated. Weighted by these shares, the average electricity consumption of the two models corresponds to 12.1 kWh/100 km and 14.8 kWh/100 km.

Table A.3: Fuel and electricity consumption of representative PHEV models in the lower medium and SUV segment in Europe.

	CS mode (from ADAC)	CD mode (from ADAC)		Average usage		
Model	**Fuel consumption (L/100 km)**	**Fuel consumption (L/100 km)**	**Electricity consumption (kWh/100 km)**	**Fuel consumption (spritmonitor.de, L/100 km)**	**CD mode drive share**	**Electricity consumption (kWh/100 km)**
BMW 225xe	7.6	2.5	17.6	4.1	69%	12.1
Mitsubishi Outlander	8.5	1.3	23.7	4.0	63%	14.8

The electricity consumption of BEVs is based on the sales-weighted average WLTP electricity consumption of the BEVs registered in the European Union and the United Kingdom in 2019 (data from EV-Volumes). By testing in more realistic driving conditions than in WLTP (including charging losses), the ADAC Ecotest reports electricity consumption values that are on average about 19% higher than the WLTP electricity consumption values. Accordingly, this study adjusts the market average WLTP electricity consumption values by this factor. Note that for NEDC electricity consumption values, the ADAC Ecotest values deviate by 30%–40%, and this is similar to the real-world factor considered for the fuel consumption of gasoline and diesel cars.

In 2019, only about 500 FCEVs were registered in the European Union and the United Kingdom, and almost all of these were either the Toyota Mirai or Hyundai Nexo (Díaz et al., 2020). Accordingly, these two models were used as representatives for the lower medium and SUV segments, respectively. The ADAC Ecotest hydrogen consumption values are considered as real-world values, and they are 25%–33% higher than the NEDC values.

United States

The fuel and electricity consumption values are based on EPA's 5-cycle test values. For gasoline ICEV passenger cars and SUVs,[17] the sales-weighted average fuel consumption of model year 2019 vehicles is directly derived from the EPA's Automotive Trends Report (U.S. Environmental Protection Agency, 2021).

Table A.4. Average real-world fuel and electricity consumption values for passenger cars and SUVs registered in the United States in 2019.

Fuel (L or kg) and electricity (kWh) consumption per 100 km	Passenger cars	SUVs
Gasoline ICEV	7.8 L	9.7 L
PHEV	2.5 L + 10.6 kWh	3.5 L + 17.6 kWh
BEV	17.3 kWh	24.0 kWh
FCEV	0.9 kg	1.1 kg

For PHEVs, the EPA's Fuel Economy Guide provides values for the fuel and electricity when driving only on fuel and only on electricity (U.S. Environmental Protection Agency & U.S. Department of Energy, 2020). As the fuel and electricity consumption of the actual CD mode is not provided, this study uses the values reported for driving only on electricity. Note that the methodology is thus different from the Europe part, in which the CD mode values can be used. For both, the values of the Honda Clarity (17 kWh variant) are found to be similar to the sales-weighted average of passenger car PHEVs in 2019 (data from EV-Volumes). Similarly, the fuel and electricity consumption of the Mitsubishi Outlander (12 kWh variant) reflects the sales-weighted average PHEV in the SUV segment. Accordingly, these models are considered as representatives for passenger cars and SUVs.

In order to weight the EPA's fuel and electricity consumption when driving only on fuel and only on electricity by the respective shares in real-world usage, average user reported fuel consumption data from the EPA's website MyMPG was used (U.S. Environmental Protection Agency & U.S. Department of Energy, 2021). With an average real-world fuel consumption of 2.5 L/100 km for the Honda Clarity and 3.5 L/100 km for the Mitsubishi Outlander, the share of driving on electricity is 55% and 63%.

An earlier analysis of the MyMPG data results in similar fuel consumption and thus electric drive shares for the two models (Plötz et al., 2020). Weighting the EPA electricity consumption values by these electric drive shares results in average electricity consumption of 10.6 kWh/100 km and 17.6 kWh/100 km.

17 Including SUVs from the regulatory classes of cars and trucks.

Table A.5. Fuel and electricity consumption of representative PHEV models in the passenger car and SUV segment in the United States.

Model	Combustion engine driving (from EPA)	Electric driving (from EPA)	Average usage	
	Fuel consumption (L/100 km)	Electricity consumption (kWh/100 km)	Fuel consumption (from MyMPG, in L/100 km)	Electricity consumption (kWh/100 km)
Honda Clarity	5.6	19.3	2.5	10.6
Mitsubishi Outlander	9.4	28.0	3.5	17.6

The average electricity consumption of BEVs, including charging losses, is based the values for individual models in the EPA's Fuel Economy Guide (U.S. Environmental Protection Agency & U.S. Department of Energy, 2020) weighted by their sales in the United States in 2019 (data from EV-Volumes).[18]

For FCEVs, the EPA hydrogen consumption values of the Toyota Mirai and Hyundai Nexo represent passenger cars and SUVs. These two and the fuel cell electric variant of the Honda Clarity, which has the same EPA hydrogen consumption as the Toyota Mirai, are the only FCEV models for sale in the United States.

China

The average real-world consumption of gasoline ICEVs in China is based on the segment-specific average NEDC values in 2019 (China Automotive Technology and Research Center, 2020) and adjusted with an average real-world deviation of 34%, as observed by user-reported fuel consumption values (Yang & Yang, 2018).

Table A.6. Average real-world fuel and electricity consumption values for cars registered in China in 2019.

Fuel (L or kg) and electricity (kWh) consumption per 100 km	A0	A	SUV
Gasoline ICEV	7.2 L	7.9 L	9.2 L
PHEV	—	5.8 L + 4.1 kWh	7.0 L + 5.7 kWh
BEV	19.7 kWh	20.4 kWh	21.7 kWh
FCEV	—	1.0 kg	1.2 kg

The real-world fuel consumption of the most popular PHEV models in China was investigated by (Plötz et al., 2020). When weighting these values by the 2019 sales in the A and SUV segment (data from China EV100), it is found that the average real-world of PHEVs in the A and SUV segments are similar to the values reported for the Roewe ei6 and BYD Song, respectively. Therefore, these models are used as representatives for the two segments.

For the Roewe ei6 and BYD Song, the average real-world fuel consumption as reported on the Chinese mobile application XiaoXiongYouHao corresponds to 5.8 L/100 km and 7.0 L/100 km, respectively (XiaoXiongYouHao, 2021). Following the methodology of Plötz et al. (2020), the real-world fuel consumption when driving only on fuel is estimated with the electric drive share weighted NEDC fuel consumption values of 1.5 L/100 km for the Roewe ei6 and 1.4 L/100 km for the BYD Song, the NEDC electric ranges of 53 km and 81 km, respectively, and a real-world to NEDC fuel consumption deviation of +50%. The latter is based on the average deviation of the real-world fuel consumption of full hybrid electric vehicles (Dornoff et al., 2020). As shown in Table A.7,

18 Note than Tesla Model 3 (all variants) corresponds to 72% of BEVs in the passenger car segment in 2019, while Tesla Model X represents 57% of the BEVs in the SUV segment.

driving the Roewe ei6 and BYD Song only on fuel is estimated to correspond to a real-world fuel consumption of 7.0 L/100 km and 8.9 L/100 km. With the fuel consumption when only driving on fuel and the average user-reported fuel consumption values, the shares of driving on electricity are estimated as 17% and 21%. For the average use of other PHEV models in China, similar electric drive shares are found (Plötz et al., 2020). Note that the share of driving on electricity, which is also considered for PHEVs in the United States, is a different measure than the share of driving in the mixed combustion engine and electric CD mode considered in the Europe part.

Table A.7. Estimated real-world fuel and electricity consumption of representative PHEV models in the A and SUV segments in China.

Model	Combustion engine driving	Electric driving	Average usage	
	Fuel consumption (L/100 km)	Electricity consumption (kWh/100 km)	Fuel consumption (XiaoXiongYouHao, L/100 km)	Electricity consumption (kWh/100 km)
Roewe ei6	7.0	23.4	5.8	4.1
BYD Song	8.9	26.6	7.0	5.7

The real-world electricity consumption of the two models during electric driving is estimated with the useable battery capacity, which is assumed to be 95% of the manufacturer declared total capacity of 9.1 kWh for the Roewe ei6 and 15.8 kWh for the BYD Song, divided by the real-world electric range, which in the case of PHEVs is considered to be 20% lower than the NEDC values of 53 km and 81 km. After considering additional charging losses of 15%, the electricity consumption when only driving electricity amounts to 23.4 kWh/100 km for the Roewe ei6 and 26.6 kWh/100 km for the BYD Song. With the electric-only drive shares for the Roewe ei6 and the BYD Song of 17% and 21%, respectively, the calculation concludes with average real-world electricity consumption values of 4.1 kWh/100 km and 5.7 kWh/100 km, respectively.

For BEVs, the real-world electricity consumption of A0, A, and SUV segment cars registered in 2019 is estimated with the average useable battery capacity, which is assumed to be 95% of the manufacturer declared capacity of 37.2 kWh, 52.9 kWh, and 52.3 kWh, divided by the real-world electric range, which is assumed to be 30% lower than the NEDC values of 294 km, 405 km, and 376 km (data from China EV100). With additional charging losses of 15%, the real-world electricity consumption amounts to 19.7 kWh/100 km in the A0 segment, 20.4 kWh/100 km in the A segment, and 21.7 kWh/100 km in the SUV segment.

The FCEV models in the A and SUV segments correspond to the Toyota Mirai and the Hyundai Nexo and the same real-world hydrogen consumption values as used for Europe.

India

The fuel consumption of gasoline and diesel ICEVs in India is based on the segment-specific average Modified Indian Driving Cycle (MIDC) fuel consumption values in FY 2019–20 (data from Segment Y Automotive Intelligence). For CNG cars in the hatchback segment, the fuel consumption is similarly based on the average FY 2019–20 MIDC value. Only a few CNG models in the sedan and SUV segments were available in India in FY 2019-20, and thus these segments are represented by the MIDC values of the Maruti Dzire and the Maruti Ertiga, respectively. In real-world usage, the fuel consumption of gasoline, diesel, and CNG cars is assumed to exceed the MIDC values by 34%, similar to what is observed for the NEDC values of gasoline cars in Europe (Dornoff et al., 2020) and China (Yang & Yang, 2018). The resulting real-world fuel consumption values are displayed in Table A.8.

Table A.8. Average real-world fuel and electricity consumption values for cars registered in India in FY 2019–20.

Fuel (L or kg) and electricity (kWh) consumption per 100 km	Hatchback	Sedan	SUV
Gasoline ICEV	6.4 L	6.8 L	8.2 L
Diesel ICEV	6.0 L	6.0 L	7.9 L
CNG ICEV	5.2 kg	5.0 kg	5.1 kg
BEV	16.6 kWh	19.2 kWh	15.9 kWh
FCEV	—	1.0 kg	1.2 kg

Only a few different BEV models were registered in India in FY 2019–20, and thus the Tata Tigor, Mahindra e-Verito, and Tata Nexon are used as representatives for the hatchback, sedan, and SUV segments, respectively. Their real-world electricity consumption is estimated by considering the manufacturer declared battery capacities of 21.2 kWh, 21.2 kWh, and 30.2 kWh as the useable battery capacity and dividing it by the real-world electric range, which is assumed to be 30% lower than the MIDC values of 212 km, 181 km, and 312 km. With additional charging losses of 15%, the real-world electricity consumption amounts to 16.6 kWh/100 km for the Tata Tigor, 19.2 kWh/100 km in the Mahindra e-Verito, and 15.9 kWh/100 km in the SUV segment.

The FCEV models in the sedan and SUV segments correspond to the Toyota Mirai and the Hyundai Nexo, and the same real-world hydrogen consumption values as used for Europe.

Carbon intensity of gasoline, diesel, and natural gas blends

Tables A.9 and A.10 summarize the biofuel share by volume and the average well-to-tank (WTT) and tank-to-wheel (TTW) GHG emissions intensity of gasoline, diesel, and natural gas consumed over the 15–18 year lifetimes of cars registered in Europe, the United States, China, and India in 2021 and in 2030. While Table A.9 presents the WTT and TTW carbon intensity per liter of gasoline or diesel and per kilogram of natural gas, Table A.10 displays the carbon intensities per MJ of fuel. Note that the carbon intensity values of the gasoline, diesel, and natural gas blends per liter or kilogram of fuel are not necessarily proportional to their carbon intensity per MJ, because the lower heating value and density of their components can significantly differ (Prussi et al., 2020).

Table A.9. WTT and TTW GHG emissions of the gasoline, diesel (in kg $CO_{2\ eq.}$/L) and natural gas blend (in kg $CO_{2\ eq.}$/kg) during the lifetime of 2021 and 2030 cars.

	Fuel type	Biofuel share (vol.%)	Fuel production, WTT (kg $CO_{2\ eq.}$/L) or (kg $CO_{2\ eq.}$/kg)		Fuel combustion, TTW (kg $CO_{2\ eq.}$/L) or (kg $CO_{2\ eq.}$/kg)	
			2021 cars	2030 cars	2021 cars	2030 cars
Europe	**Gasoline**	5	0.68	0.67	2.24	2.24
	Diesel	7	0.98	0.95	2.44	2.44
	Natural gas	3	0.76	0.76	2.71	2.71
United States	**Gasoline**	10	0.69	0.69	2.16	2.16
China	**Gasoline**	5	0.69	0.69	2.24	2.24
India	**Gasoline**	5–20	0.64	0.61	2.15	1.99
	Diesel	0–5	0.78	0.78	2.57	2.51
	Natural gas	0–10	0.92	0.94	2.76	2.64

Table A.10. WTT and TTW GHG emissions of the gasoline, diesel and natural gas blends in g $CO_{2\,eq.}$/MJ during the lifetime of 2021 and 2030 cars

	Fuel type	Biofuel share (vol.%)	Fuel production, WTT (g $CO_{2\,eq.}$/MJ)		Fuel combustion, TTW (g $CO_{2\,eq.}$/MJ)	
			2021 cars	2030 cars	2021 cars	2030 cars
Europe	**Gasoline**	5	21.5	21.4	70.9	70.9
	Diesel	7	27.4	26.7	68.4	68.4
	Natural gas	3	16.5	16.5	58.6	58.6
U.S.	**Gasoline**	10	22.2	22.2	69.7	69.7
China	**Gasoline**	5	21.8	21.8	70.9	70.9
India	**Gasoline**	5–20	20.5	20.2	69.1	65.4
	Diesel	0–5	21.8	21.7	71.8	70.1
	Natural gas	0–10	19.2	19.6	57.7	55.3

Europe

The EU gasoline blend currently contains 5vol.% ethanol, which is made from a mix of feedstocks that is mostly based on corn, wheat, and sugar beet (Huss & Weingerl, 2020). In line with the requirements of the *Renewable Energy Directive* (RED II; European Parliament & Council of the European Union, 2018), the share of cellulosic ethanol, for example from wheat straw, is considered to increase by 2030 (Huss & Weingerl, 2020). When considering the direct GHG emissions during production (Prussi et al., 2020) and the indirect land use-change (ILUC) emissions (Valin et al., 2015), the life-cycle GHG emissions of ethanol are not necessarily lower than those from the production and combustion of fossil gasoline (Council of the European Union, 2015).

Table A.11. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2020 and 2030 European ethanol mix compared to fossil gasoline.

	Share in ethanol mix (vol.%)		WTT, excluding ILUC (g $CO_{2\,eq.}$/MJ)		ILUC (g $CO_{2\,eq.}$/MJ)		WTW, including ILUC (g $CO_{2\,eq.}$/MJ)	
	2020	2030	2020	2030	2020	2030	2020	2030
Corn	38	34	57	57	14	14	71	71
Wheat	30	26	63	52	34	34	97	86
Sugar beet	19	19	28	28	15	15	43	43
Barley/rye	7	6	65	65	38	38	103	103
Sugar cane	2	2	24	24	17	17	41	41
Wheat straw	4	13	18	18	—	—	18	18
EU ethanol mix							73	64
Fossil gasoline							93	93

The EU average diesel blend contains 7vol.% biogenic diesel, 83vol.% of which corresponds to biodiesel (or fatty acid methyl ester, FAME) and 17vol.% of which is hydrogenated vegetable oils (HVO). As displayed in Tables A.12 and A.13, both are mostly based on rapeseed oil, palm oil, and used cooking oil (Huss & Weingerl, 2020). For biodiesel and HVO based on food crops like rapeseed oil, palm oil, soybean oil, or sunflower oil, the direct GHG emissions during their production (Prussi et al., 2020) and the ILUC emissions (Valin et al., 2015) are significantly higher than the production and combustion emission of fossil diesel (Council of the European Union, 2015). Especially in the case of palm oil and soybean oil, the life-cycle GHG emissions are two to three times higher than for the fossil fuel. In contrast, advanced biofuels based on residues and wastes such as used cooking oil offer a significant GHG emission benefit over fossil fuels. Their share in the current EU mix of the different biodiesel and HVO feedstocks reduces the average life-cycle GHG emissions of biogenic diesel.

Since biofuel feedstocks with a high risk of high ILUC emission will not count toward the 2030 targets of the *Renewable Energy Directive* (RED II; European Parliament & Council of the European Union, 2018), palm oil-based diesel is assumed to be phased out by 2030. Thereby, the life-cycle GHG emissions of the overall biodiesel and HVO mix is expected to approach the carbon intensity of fossil diesel.

Table A.12. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2020 and 2030 European biodiesel mix compared to fossil diesel.

	Share in biodiesel mix (vol.%)		WTT, excluding ILUC ($g\ CO_{2\ eq.}/MJ$)		ILUC ($g\ CO_{2\ eq.}/MJ$)		WTW, including ILUC ($g\ CO_{2\ eq.}/MJ$)	
	2020	2030	2020	2030	2020	2030	2020	2030
Rapeseed oil	52	63	51	51	65	65	116	116
Palm oil	20	0	36	—	231	—	267	—
Soybean oil	5	7	58	59	150	150	208	209
Sunflower oil	1	8	42	42	63	63	105	105
Used cooking oil	17	15	8	8	—	—	8	8
Animal fats	5	5	14	14	—	—	14	14
Other residual	—	2	—	8	—	—	—	8
Total FAME							127	98
Fossil diesel							95	95

Table A.13. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different feedstocks used in the 2020 and 2030 European HVO mix compared to fossil diesel.

	Share of HVO mix (vol.%)		WTT, excluding ILUC ($g\ CO_{2\ eq.}/MJ$)		ILUC ($g\ CO_{2\ eq.}/MJ$)		WTW, including ILUC ($g\ CO_{2\ eq.}/MJ$)	
	2020	2030	2020	2030	2020	2030	2020	2030
Palm oil	45	0	35	—	231	—	266	—
Rapeseed oil	18	54	52	52	65	65	117	117
Soybean oil	2	5	60	60	150	150	210	210
Sunflower oil	0.4	0.4	42	42	63	63	105	105
Used cooking oil	25	25	11	11	—	—	11	11
Animal fats	11	11	16	16	—	—	16	16
Other residual	—	5	—	11.1	—	—	—	11
Total HVO							150	79
Fossil diesel							95	95

The EU average natural gas blend is presented in Table A.14. In addition to natural gas that is transported via pipeline, it contains natural gas transported to Europe via ships as LNG and biomethane produced from corn, plant residues, and manure (Huss & Weingerl, 2020). The fuel blend is considered to remain constant. The fuel production (WTT) and combustion (TTW) carbon intensity of the fossil natural gas pathways are based on a recent report by a consortium of the Joint Research Center, European Council for Automotive R&D, and Concawe, the JEC (Prussi et al., 2020). In the JEC report, the methane leakage emissions during natural gas production and transport are considered with 3.8 g $CO_{2\ eq.}$/MJ for natural gas transported by pipeline and 3.3 g $CO_{2\ eq.}$/MJ for natural gas transported by ship. In both cases, these emissions are only half as high as the 7.8 g $CO_{2\ eq.}$/MJ (0.26 g CH_4/MJ) the GREET tool (Argonne National Laboratory, 2020) considers based on 2018 study by the Environmental Defense Fund (EDF, Alvarez et al., 2018). As the latter is based on more recent data and estimated to be similar also on a global level (Hmiel et al., 2020), the WTT carbon intensity of the JEC report is adjusted with the methane leakage emissions from the EDF-based numbers in the GREET tool.

For the corn, plant residues, and manure biomethane pathways, the direct production emissions Prussi et al., 2020) and the ILUC emissions of corn silage (Valin et al., 2015) are considered.

Table A.14. Share, WTT (excluding ILUC), ILUC, and total WTW GHG emissions of different natural gas and biomethane pathways in the EU natural gas mix.

	Share (vol.%)	WTT, excluding ILUC (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	WTW, including ILUC (g $CO_{2\ eq.}$/MJ)
Natural gas (pipeline)	77.7	15	—	75
Natural gas (ship)	18.9	22	—	82
Corn-based biomethane	1.4	26	21	47
Waste-based biomethane	1.4	10	—	10
Manure-based biomethane	0.7	-103	—	-103

The 20-year GWP of the EU natural gas blend is estimated by considering the 20-year instead of the 100-year GWP of the methane leakage emissions during natural gas production. With a 20-year GWP of 85 g $CO_{2\ eq.}$/g CH_4 instead of 30 g $CO_{2\ eq.}$/g CH_4 (IPCC, 2013), the GWP of these emissions corresponds to 22 g $CO_{2\ eq.}$/MJ instead of 8 g $CO_{2\ eq.}$/MJ. Thereby, the carbon intensity of the whole natural gas blend increases by 18%, from 75 g $CO_{2\ eq.}$/MJ to 89 g $CO_{2\ eq.}$/MJ.

United States

Despite higher ambitions for the volumes of cellulosic and other advanced biofuels in the federal *Renewable Fuel Standard*, as foreseen in the 2007 *Energy Independence and Security Act*, their shares only increased from 0.8% in 2015 to 1.5% in 2020 (U.S. Department of Energy, 2021). The ethanol share of 10% in the U.S. gasoline blend thus almost entirely corresponds to corn ethanol. In Table A.15, the GHG emissions for the production of corn ethanol (excluding ILUC) are derived from the GREET tool (Argonne National Laboratory, 2020), and the ILUC emissions of 26 g $CO_{2\ eq.}$/MJ are based on the numbers used by the EPA (U.S. Environmental Protection Agency, 2010). The WTW GHG emissions of the average fossil gasoline blend used in the United States are considered with the same 93 g $CO_{2\ eq.}$/MJ as for Europe (U.S. Environmental Protection Agency, 2010).

Table A.15. Share, WTT (excluding ILUC), ILUC, TTW, and WTW GHG emissions of fossil gasoline and corn ethanol in the gasoline blend in the United States.

	Share (vol.%)	WTT, excluding ILUC (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
Fossil	90.0	18	—	75	93
Ethanol	10.0	47	26	—	73

China

The average gasoline blend in China in 2011–2019 contained about 2% ethanol, which was almost entirely based on domestic corn (U.S. Department of Agriculture, 2020). In this study, the ethanol share is assumed to increase to 5% for the whole 2020–2050 timeframe. The GHG emissions of the production of corn ethanol in China (excluding ILUC) of 50 g $CO_{2\ eq.}$/MJ are derived from the GREET tool (Argonne National Laboratory, 2020) that was adjusted for the 2019 electricity mix in China (International

Energy Agency, 2020). For the ILUC GHG emissions, the same 26 g $CO_{2\ eq.}$/MJ as used for the United States is considered (U.S. Environmental Protection Agency, 2010). For fossil gasoline, the same GHG emissions as for the European and United States' fossil gasoline blends are considered.

Table A.16. Share, WTT (excluding ILUC), ILUC, TTW, and WTW GHG emissions of fossil gasoline and corn ethanol in the gasoline blend in China.

	Share (vol.%)	WTT, excluding ILUC (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
Fossil	95.0	20	—	73	93
Ethanol	5.0	50	26	—	76

India

With the 2018 *National Policy on Biofuels*, the Government of India aims to increase the ethanol share to 20% of the gasoline blend and the biogenic diesel shares to 5% of the diesel blend (Pavlenko & Searle, 2019). As the policy focuses on ethanol made from molasses, energy crops, and residues, and waste-based diesel, the ILUC GHG emissions and other negative environmental and social impacts of the program are significantly lower than for the mostly food-based biofuel policies in Europe and the United States, for instance. Although the required resources are available in India in principle, development of an advanced biofuels industry and the corresponding biofuel production capacities is considered to require more time than the foreseen target year of 2030. Based on an earlier ICCT study (Pavlenko & Searle, 2019), this study assumes the targets of the *National Policy on Biofuels* are realized, but only by 2040.

Tables A.17 and A.18 present the estimated shares of molasses-, residues-, and energy crop-based ethanol in the 2020, 2030, and 2040 gasoline mix, as well as the shares of used cooking oil- and municipal solid waste-based diesel in the respective diesel blends. Until they reach their final values, the shares of residues- and energy crop-based ethanol and biodiesel based on used cooking oil (UCO) and municipal solid waste (MSW) are considered to increase exponentially. While the WTT and TTW emissions of fossil gasoline and diesel are considered to be similar to the European and U.S. fossil fuel blends, the production and ILUC GHG emissions of molasses-based ethanol are based on an earlier ICCT analysis (El Takriti et al., 2017). For residues- and energy-crop-based ethanol, the GHG emissions of production and ILUC are derived from the GREET tool (Argonne National Laboratory, 2020), adjusted for the 2019 electricity mix in India (IEA, 2020). The production GHG emissions of UCO-based biodiesel are assumed to be similar to Europe. For MSW-based diesel, they are based on Suresh (2016).

Table A.17. Share, WTT (excluding ILUC), ILUC, TTW, and total WTW GHG emissions of different ethanol feedstocks and fossil gasoline used in the Indian gasoline mix.

	Share (vol.%)			WTT, excluding ILUC (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
	2020	2030	2040				
Molasses	5.0	5.0	5.0	9	32	—	41
Residues	0.0	3.8	10.0	1.0	-0.6	—	0.4
Energy crop	0.0	1.8	5.0	6.5	-2.9	—	3.6
Fossil gasoline	95.0	89.4	80.0	20	—	73	93

Table A.18. Share, WTT (excluding ILUC), ILUC, TTW, and total WTW GHG emissions of different biodiesel feedstocks and fossil diesel used in the Indian diesel mix.

	Share (vol.%)			WTT, excluding ILUC (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
	2020	2030	2040				
UCO	0.0	2.8	2.8	8	—	—	8
MSW	0.0	1.0	2.2	33	—	—	33
Fossil diesel	100.0	96.2	95.0	22	—	73	95

As presented in Table A.19, the current natural gas mix in India corresponds to a 50:50 mix of domestically produced and imported natural gas; the latter is in the form of LNG and is transported to India by ship. Due to a strongly increasing demand for natural gas, especially in the power sector, an increasing share of the natural gas supply is considered to be imported as LNG. In addition, it is projected that up to 10% of the natural gas used in India could be biomethane by 2040 (IEA, 2021). While the production (WTT) and combustion (TTW) emissions of domestic natural gas and imported LNG in India are considered with the same factors as for Europe (compare Table A.14), the biomethane production in India is assumed to be entirely sewage-based biomethane (Prussi et al., 2020), and thus no ILUC emissions are considered. As a result, the life-cycle GHG emissions of the natural gas mix in India decrease from 79 g $CO_{2\ eq.}$/MJ in 2020 to 74 g $CO_{2\ eq.}$/MJ in 2040. For the average carbon intensity over the lifetime of cars registered in 2021 and projected to be registered in 2030, this corresponds to life-cycle GHG emissions of 77 g $CO_{2\ eq.}$/MJ and 75 g $CO_{2\ eq.}$/MJ (Table A.10).

Table A.19. Share, WTT, TTW, and total WTW GHG emissions of different natural gas and biomethane pathways in the Indian natural gas mix.

	Share (vol.%)			WTT (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
	2020	2030	2040			
Domestic natural gas (pipeline)	50	40	35	15	60	75
Imported natural gas (LNG, ships)	50	55	55	22	60	82
Biomethane (sewage-based)	0	5	10	22	—	22

As described for the EU natural gas mix, the 20-year GWP of the Indian natural gas blend is estimated by considering the 20-year GWP of the methane leakage emissions during natural gas production, instead of the 100-year GWP. Thereby, the carbon intensity of the whole natural gas blend in 2020 and 2040 increases to 93 g $CO_{2\ eq.}$/MJ and 87 g $CO_{2\ eq.}$/MJ. Finally, the 20-year GWP lifetime average carbon intensity of the natural gas mix for 2021 and 2030 cars increases to 91 g $CO_{2\ eq.}$/MJ and 88 g $CO_{2\ eq.}$/MJ, respectively.

Methane and N_2O emissions from the vehicles

The TTW emissions in Table A.9 consider a complete oxidation of the carbon content of the fuel to CO_2 (Prussi et al., 2020). In reality, however, this reaction is incomplete, and results in some emissions of methane (CH_4), other hydrocarbons, and particulate matter (PM). Among these, the methane slip emissions are especially significant, as the 100-year GWP of methane is 30 times higher than for CO_2 (1 g CH_4 = 30 g $CO_{2\ eq.}$; IPCC, 2013). Based on studies on Euro 6 cars in Europe (Prussi et al., 2020); Valverde & Giechaskiel, 2020; Vojtíšek-Lom et al., 2018; Hagos & Ahlgren, 2018), the methane emissions from gasoline, diesel, and CNG cars are considered with 5 mg CH_4/km, 9 mg CH_4/km, and 60 mg CH_4/km. The other hydrocarbons and PM emissions are not considered in this study.

In addition, the combustion of gasoline, diesel, and natural gas is related to nitrous oxide (N_2O) emissions. Due to a 265 times higher 100-year GWP than CO_2 (1 g N_2O = 265 g $CO_{2\ eq.}$), even small amounts of N_2O emissions can significantly contribute to the overall GHG emissions (IPCC, 2013). For gasoline, diesel, and CNG cars, this study considers emissions of 2 mg N_2O/km, 15 mg N_2O/km, and 2 mg N_2O/km, respectively (Prussi et al., 2020; Valverde & Giechaskiel, 2020; Suarez-Bertoa & Astorga, 2018; Vojtíšek-Lom et al., 2018).

Combining the methane and N_2O emissions results in additional GHG emissions of 0.7 g $CO_{2\ eq.}$/km for gasoline, 4.2 g $CO_{2\ eq.}$/km for diesel, and 2.3 g $CO_{2\ eq.}$/km for CNG cars. These emissions are assumed to be the same for cars in all regions.

Carbon intensity of electricity

The carbon intensity of the electricity consumed for charging BEVs and PHEVs, and for producing electricity-based hydrogen and liquid e-fuels, is based on the IPCC's life-cycle GHG emissions of the different electricity generation technologies in Table A.20 (IPCC, 2011**;** Christensen & Petrenko, 2017). For renewable energy, the life-cycle GHG emissions mostly correspond to the construction of the powerplants. With a continuous decarbonization of industry in general and the electricity grid in particular, these are expected to decrease for future power plants (Pehl et al., 2017). In a conservative approach, however, this study considers them to remain constant.

Table A.20. Global average life-cycle GHG emissions of electricity generation technologies.

		g $CO_{2\ eq.}$/kWh	g $CO_{2\ eq.}$/MJ
Fossil	**Coal**	1,001	278
	Oil	840	233
	Natural gas	469	130
	Nuclear energy	16	4
Renewable	**Biopower**	230	64
	Geothermal energy	45	13
	Solar photovoltaic (PV)	46	13
	Concentrated solar power (CSP)	22	6
	Wind energy	12	3
	Marine/ocean	8	2
	Hydropower	4	1

As highlighted in **Section 2.5**, the life-cycle carbon intensities of the electricity mix the European Union, the United States, China and India are derived by weighting the emission factors of the different electricity generation technologies in Table A.20 by their projected shares in the Stated Policy Scenario (STEPS) and the Sustainable Development Scenario (SDS) in the IEA's World Energy Outlook (International

Energy Agency, 2020). As for the fuel mixes, the EU electricity mix is considered representative for Europe. For the carbon intensity of the electricity mix "at the plug", these values are adjusted by transmission and distribution losses in the electric grid of 6% (of output) in the European Union and the United States, 5% in China and 19% in India (IEA, 2021). The resulting life-cycle GHG emissions in the four regions are displayed in **Figure 2.1**. Note that the IEA's projections only cover the period from 2020 to 2040. For the period of 2040 to 2050, the average life-cycle carbon intensity is considered to decrease with the same rate as in the 2030 to 2040 period. In the STEPS projections, the decrease is capped when reaching the life-cycle emission levels of the regional 100% renewables mixes that are described in the following paragraphs.

For the production of electricity-based hydrogen and e-fuels, and also for assessing the life-cycle GHG emissions of driving a BEV with renewable electricity, this study considers regionally differing mixes of solar and wind power. For the United States and China, a 50:50 mix of solar and wind energy is assumed. The EU renewables mix, meanwhile, contains a higher share of wind (33:67) and the Indian mix is more based on solar energy (67:33).

Table A.21 presents the GHG emissions of the average electricity mix over the lifetime of 15 to 18 years of cars registered in 2021 and in 2030. They are based on the development of the carbon intensity as displayed in **Figure 2.1** and consider the decrease of the annual mileage.

Table A.21. Life-cycle GHG emissions of the vehicles' lifetime average electricity mix, for 2021 and 2030 cars, based the IEA's Stated Policy Scenario (STEPS), the Sustainable Development Scenario (SDS), and a regionally adjusted renewable electricity mix of solar and wind energy.

		Life-cycle carbon intensity of electricity consumption (g $CO_{2\ eq.}$/kWh)				
		2021 cars		2030 cars		
	Vehicle lifetime	STEPS	SDS	STEPS	SDS	Renewables
EU	18 years	199	164	130	96	23
United States	18 years	357	239	287	113	29
China	15 years	622	509	527	285	29
India	15 years	746	561	545	259	35

To assess the carbon intensity of the electricity mix for the sensitivity analysis in individual European countries, the life-cycle carbon intensities of the electricity generation technologies in Table A.20 are weighted by their projected shares in the central scenario in the JRC's POTEnCIA model (Mantzos et al., 2019). Also here, the carbon intensity of electricity production is adjusted by transmission and distribution losses in the electricity grid (IEA, 2021). Similar to the IEA's SDS, the central scenario in the POTEnCIA model only considers the effects of policies and measures introduced until the end of 2017. Accordingly, for the European Union and the United Kingdom, the resulting vehicle lifetime average carbon intensity for cars registered in 2021 is 197 g $CO_{2\ eq.}$/kWh, very similar to the 199 g $CO_{2\ eq.}$/kWh derived with the IEA's STEPS (only European Union, Table A.21). On an individual country level, the vehicle lifetime average carbon intensities for cars registered in 2021 are 303 g $CO_{2\ eq.}$/kWh for Germany, 125 g $CO_{2\ eq.}$/kWh for the United Kingdom, 35 g $CO_{2\ eq.}$/kWh for France, 130 g $CO_{2\ eq.}$/kWh for Italy, and 107 g $CO_{2\ eq.}$/kWh for Spain.

Carbon intensity of hydrogen

In all regions, this study compares hydrogen produced from natural gas, both grey hydrogen and blue hydrogen, which is produced in combination with CCS, with hydrogen produced from renewable electricity (green hydrogen). For China, the carbon intensity of hydrogen produced via coal gasification (black hydrogen) is also assessed. As presented in Table A.22, the carbon intensity of the different hydrogen pathways varies by more than one order of magnitude, between 11–16 g $CO_{2\ eq.}$/MJ for green hydrogen and 175 g $CO_{2\ eq.}$/MJ for black hydrogen. The lower heating value of hydrogen is considered with 120 MJ/kg.

Table A.22. 100-year and 20-year global warming potential (GWP, in g $CO_{2\ eq.}$ per MJ hydrogen) of the life-cycle GHG emissions of the different hydrogen pathways in Europe, the United States, China, and India.

	Renewable electricity	Natural gas		Natural gas (with CCS)		Coal	
(g $CO_{2\ eq.}$/ MJ)	100-year GWP	100-year GWP	20-year GWP	100-year GWP	20-year GWP	100-year GWP	20-year GWP
Europe	10.8	113	132	28	47	—	—
United States	13.5	101	120	35	54	—	—
China	13.5	111	130	35	54	175	190
India	16.2	115	134	35	54	—	—-

Electricity-based hydrogen (green hydrogen)

When produced via electrolysis, the life-cycle GHG emissions of hydrogen are determined by the carbon intensity of the used electricity and the energy efficiency of the electrolysis. Since the energy efficiency of the electrolysis is considered to increase from a current value of 65% (Prussi et al., 2020) to 70% in 2030, and then further to 80% in 2050 (Heinemann et al., 2019), this study considers an average value of 70%. This corresponds to 1.43 MJ electricity per MJ hydrogen. In addition the electrolysis itself, the compression of hydrogen and its dispensing at the retail side is considered with an energy loss of 0.25 MJ per MJ hydrogen (Prussi et al., 2020). Altogether, electrolysis-based hydrogen corresponds to an energy demand of 1.68 MJ electricity per MJ hydrogen, which corresponds to 56 kWh electricity per kg hydrogen. When produced from the regionally different renewable electricity mixes in the European Union, the United States, China, and India in Table A.21, the carbon intensities of green hydrogen are 11–16 g $CO_{2\ eq.}$/MJ.

Note that there are considerable energy and hydrogen losses corresponding to the storage and long-distance transport, for example as compressed hydrogen in pipelines or as liquefied hydrogen in ships, and these are not included in this analysis.

Natural gas-based hydrogen (grey hydrogen)

For the United States, China, and India, the production of hydrogen from natural gas is based on the GREET tool (Argonne National Laboratory, 2020), adjusted by the 2019 electricity in China and India (IEA, 2020). As described in **Section 2.6**, these consider the upstream methane emissions of natural gas production as reported by the EDF (Alvarez et al., 2018). For Europe, these values are used to adjust the upstream methane emissions considered in the JEC study (Prussi et al., 2020). Based on the 20-year GWP of the EDF- and GREET-based upstream methane emissions, also the 20-year GWP of hydrogen production from natural gas is determined.

Natural gas-based hydrogen with CCS (blue hydrogen)

The carbon intensity of hydrogen produced from natural gas in combination with CCS generally corresponds to the midrange value on a range of 28–42 g $CO_{2\ eq.}$/MJ found in a literature review in a recent ICCT study (Baldino et al., 2020). In Europe, a slightly lower value of 28 g $CO_{2\ eq.}$/MJ is considered. This is based on two assumptions: (1) that in the future, blue hydrogen will count toward the EU's *Renewable Energy Directive* (RED II); and (2) that the same threshold as for renewable hydrogen will be applied, which is 30% of the carbon intensity of the fossil comparator of 94 g $CO_{2\ eq.}$/MJ. These values are considered to include the same upstream methane leakage emissions from natural gas production as for natural gas-derived hydrogen without CCS. With the 20-year GWP of the methane emissions, the carbon intensity increases to 47 g $CO_{2\ eq.}$/MJ in Europe and 54 g $CO_{2\ eq.}$/MJ in the other regions.

Coal-based hydrogen (black hydrogen)

Based on the GREET tool (Argonne National Laboratory, 2020), adjusted by the 2019 electricity in China (International Energy Agency, 2020), the high GHG emissions of producing hydrogen via the gasification of coal amount to 175 g $CO_{2\ eq.}$/MJ. In this pathway, the production of coal itself and its gasification to hydrogen correspond to methane emissions of 0.27 g CH_4 per produced MJ of hydrogen, a similar level as for the natural gas pathway. With these methane emissions, the 20-year GWP of coal-based hydrogen is estimated as 190 g $CO_{2\ eq.}$/MJ.

Carbon intensity of e-fuels

E-fuels, or electrofuels, are produced from electrolysis-based hydrogen and CO_2 that is either sourced from point sources, in other words exhaust gases, or directly from the air. In principle, the CO_2 emitted during the combustion of e-fuels is offset by the CO_2 captured upstream to produce the fuel. The net GHG emissions of e-fuels thus solely correspond to the energy-related emissions for electrolysis, CO_2 capture, and fuel synthesis. In total, the three production steps correspond to an energy demand of about 2 MJ/MJ e-fuel, relatively independent from producing the fuel in a Fischer-Tropsch synthesis or a methanol pathway (Heinemann et al., 2019; Prussi et al., 2020). Thereby, the life-cycle carbon intensities of the different renewable electricity mixes in the European Union, the United States, China, and India in Table A.21 would correspond to e-fuels with carbon intensities of 13–19 g $CO_{2\ eq.}$/MJ.

A.3 BATTERY

Section 2.4 detailed the study's assessment of the GHG emissions corresponding to battery production. The following paragraphs discuss and estimate how these would be reduced by considering also second-life usage and recycling of the batteries.

Second-life usage

Currently used lithium-ion batteries are expected to provide 1,500 to 15,000 charge and discharge cycles until only 80% of the initial capacity remains (Few et al., 2018). This wide range reflects the fact that the cycle life of these batteries is uncertain and varies with the electrode materials, as well as with the usage conditions, such as charge and discharge rate, storage time and temperature. For NMC532-graphite cells, long-term charge and discharge experiments show 90-95% of the initial capacity even after 3,000 full charge and discharge cycles (Harlow et al., 2019). For BEVs with a range of 200–400 km, 3,000 cycles correspond to 600,000–1,200,000 km, which is several times more than the average passenger car's lifetime mileage (compare lifetime mileage in Section A.1). The batteries could thus be used in second-life applications e.g., to stabilize the integration of renewable energies in the power grid, for years or even decades. With this prolonged use phase only a share of the life-cycle GHG emissions of battery production would need to be accounted for in the vehicle cycle.

Recycling

At the end of life of 2021 and 2030 electric vehicles, which is in the 2035–2050 timeframe, batteries are expected to be recycled to a large extent (Slowik et al., 2020). The GHG emission impact of using recycled instead of raw battery materials strongly depends on the electrode materials and the applied recycling processes (Ciez & Whitacre, 2019). For NMC622-graphite batteries, for instance using cobalt, nickel, and where applicable also lithium, from pyrometallurgical, inorganic or organic acid hydrometallurgical recycling is estimated to lower the production GHG emissions displayed in **Tables 2.3 and 2.4** by up to 14%–25% (Argonne National Laboratory, 2020).[19] For a full recycling of the NMC cathode material from direct recycling, the production GHG emissions could even be cut by half. Given the regulatory and technological uncertainty about the future recycling processes at the end of life of 2021 and 2030 cars, the GHG emission benefit of battery recycling is not considered in this study.

19 These numbers correspond to the European Commission's proposed recycling target of 95% for Co and Ni, and 70% for Li.