WORKING PAPER 22

VEHICLE FUEL ECONOMY IN MAJOR MARKETS 2005-2019

GLOBAL FUEL ECONOMY INITIATIVE
FOR ZERO CARBON VEHICLES BY 2050

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Abstract

This report presents the latest update to the Global Fuel Economy Initiative's biannual benchmarking report on light-duty vehicle sales. The report tracks the progress of fuel economy of new light-duty vehicles, providing the latest insights based on a rich dataset covering about 85-90% of global light-duty vehicle sales and extending from 2005 to 2019. It leverages these data and IEA modelling to inform policy makers on the policies that would be needed to align the pace of light-duty vehicle efficiency improvements with climate ambitions. To inform the Global Fuel Economy Initiative (GFEI) targets, which go beyond tailpipe emissions, this report extends the scope of analysis from rated fuel economy and tailpipe emissions to consider the current and potential performance of different light-duty vehicle fuel-powertrain options on a well-to-wheel basis; quantifying greenhouse gas emissions incurred in producing, transporting and delivering both conventional transport fuels (derived from oil and gas), and energy carriers such as electricity and hydrogen.

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Executive summary

Achieving the 2030 target of the Global Fuel Economy Initiative requires almost tripling the speed of progress since 2005

The aim of this report is to track the progress of fuel economy of new light-duty vehicles across the globe to inform policy makers on the effectiveness of relevant policies in place towards the pace of fuel economy improvements to be in line with climate ambitions. The report measures progress against the Global Fuel Economy Initiative (GFEI) target of halving the fuel consumption of new light-duty vehicles by 2030, relative to 2005.

The urgency of policy action is underlined by the fact that fuel economy progress is stalling. The average rated fuel consumption of new light-duty vehicles fell by only 0.9% between 2017 and 2019 (the latest year for which data are available), to 7.1 litres of gasoline equivalent per 100 kilometres (Lge/100 km). This drop is far smaller than the 1.8% annual average reduction between 2010 and 2015.

The three major car markets – the People's Republic of China (hereafter, "China"), the European Union and the United States – accounted for 60% of global sales of light-duty vehicles in 2019, which totalled 90 million, down 7% from 2017. Between 2017 and 2019, average rated fuel consumption rose in Europe, as the European Union's CO_2 emission regulations did not require any further improvement until 2020, when rated emissions from new vehicles declined by more than 10% year-on-year. In the United States, the average fuel consumption of new light-duty vehicles remained unchanged between 2017 and 2019, following a relaxation of fuel economy standards. In contrast, average fuel consumption declined in China, driven by fuel economy standards, and in emerging markets and developing economies.

Total improvements are significantly lower than the 2.8% yearly fuel economy improvements needed to meet the Global Fuel Economy Initiative target of halving the fuel consumption of new light-duty vehicles by 2030 relative to 2005. Given slow progress to date, achieving this target will require fuel consumption to decrease by 4.3% per year on average from 2019 to 2030 – a near tripling of the average annual pace of improvement since 2005. Such a transformation in fuel consumption trends can be brought about only by stronger policies that increase the market shares of efficient electric cars as well as global adoption of state-of-the-art efficiency technologies in internal combustion engines.

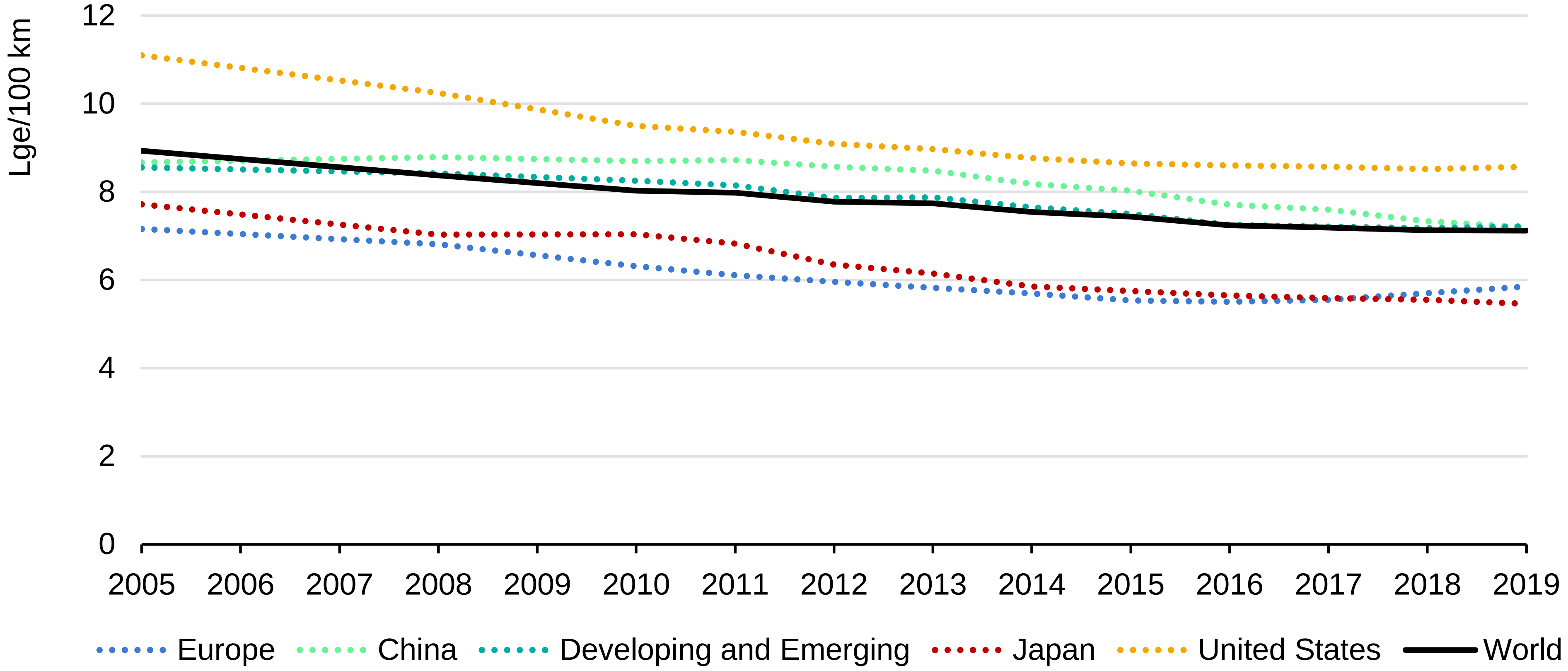
The importance of electric vehicles is underlined by the fact that CO_2 emissions fell faster than fuel economy between 2017 and 2019 because market penetration of electric vehicles rose. Global average rated CO_2 emissions in 2019 were 167 grammes of CO_2 per km (g CO_2/km), a 1.6% decrease from 2017.

To meet the GFEI 2030 target, countries need to align legislation on fuel economy with their climate pledges. Countries' current and stated policies are not sufficient to meet the GFEI 2030 target, as shown by the International Energy Agency (IEA) Stated Policies Scenario. If countries align their fuel economy standards and market adoption of zero-emission vehicles with their plans to achieve their nationally determined contributions and/or net zero emissions pledges, however – as shown in the IEA Announced Pledges Scenario – they can meet the 2030 GFEI target.

Only the Net Zero Emissions by 2050 Scenario meets the GFEI 2050 target. The GFEI's long-term, more ambitious target is to reduce well-to-wheel emissions of light-duty vehicles by 90% by 2050, relative to 2005. In the Announced Pledges Scenario, these emissions decline by only about 40% by 2050. Meeting the GFEI goal for 2050 requires an energy and transport sector transformation of the scale, speed and depth depicted in the IEA Net Zero Emissions by 2050 Scenario. The fact that only the Net Zero Scenario can achieve this ambition highlights the need for rapid, targeted action on many fronts, including improving vehicle efficiency; deploying zero-emission vehicles; decarbonising electricity and hydrogen supply; encouraging shifts to other modes of transport; and managing travel demand.

Improvements in average new fuel consumption and tailpipe CO_2 emissions are stalling

Average fuel consumption of new light-duty vehicle sales, 2005-2019

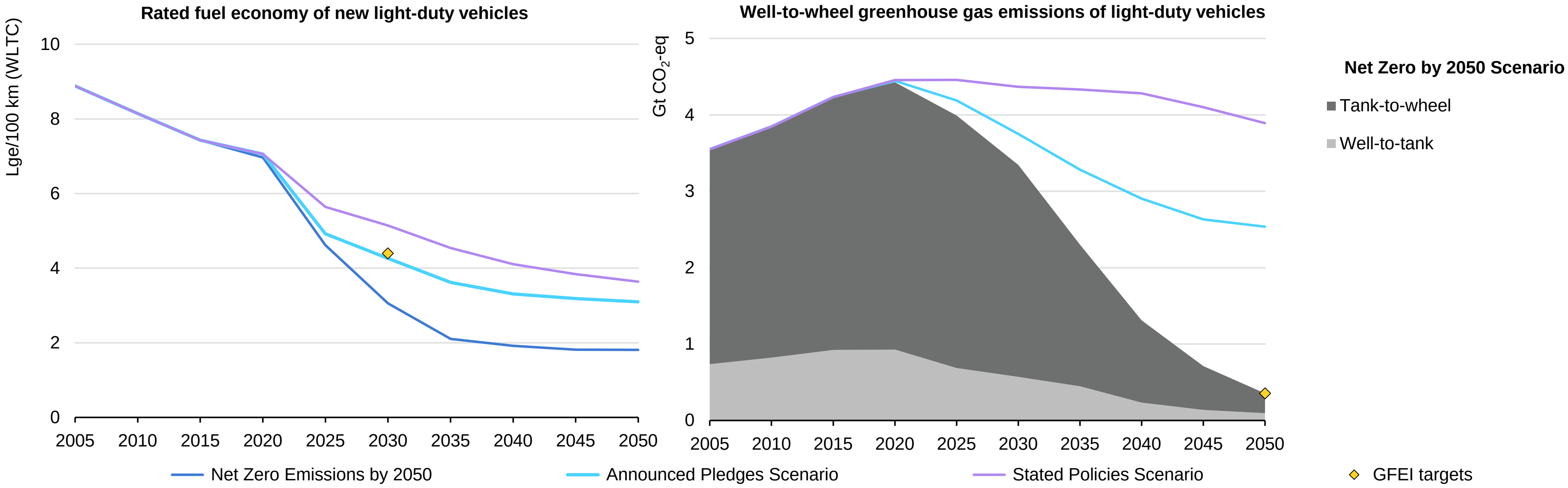


Notes: Rated fuel consumption was converted from national test cycles to estimated performance on the Worldwide Harmonized Light-Duty Test Cycle using the zero-intercept conversion equations developed by the International Council on Clean Transportation (2014). The GFEI dataset covers 85-90% of the light-duty vehicle market. EU27 refers to the current 27 member countries of the European Union. Developing and Emerging refers to emerging markets and developing economies (Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, the Russian Federation and Ukraine).

Source: IEA analysis based on IHS Markit database.

IEA Scenarios highlight the policy ambition and technology progress needed to meet GFEI targets

Trajectories of rated fuel economy (left) and well-to-wheel emissions of light-duty vehicles against GFEI targets and IEA Scenarios



Note: Rated (tank-to-wheel) fuel economy normalised globally to the Worldwide Harmonized Light-Duty Test Cycle (WLTC).
Source: [IEA Mobility Model](#) (2021 September version).

Vehicles are getting larger and more powerful, eroding progress on fuel economy. But even if they were not, we still would not be on track to achieving the 2030 GFEI fuel economy target.

Improvements in fuel economy have slowed recently for two main reasons: vehicles are becoming ever larger and more powerful, and efficient engines have not been adopted quickly enough to compensate. At the same time, efficiency gains in conventional internal combustion engine vehicles are slowing down as their remaining efficiency potential becomes more expensive and technically difficult to exploit.

Larger and more powerful cars

Between 2010 and 2019, sales-weighted average new light-duty vehicles became 6.2% heavier, 20% more powerful and had a 7% larger footprint, with the most rapid increases in China. A key cause of this trend has been a shift from cars (sedans) to SUVs and light trucks. As SUVs are larger and heavier than conventional cars, they require more power and consume on average nearly one-third more fuel than a medium-sized car. SUVs' global share of new light-duty vehicle sales rose from 20% in 2010 to 44% in 2019. Even in markets with high SUV sales, such as the United States, SUVs continue to claim a larger share of the market. In Japan, on the other hand, the trend towards larger and heavier vehicles has been far more muted, in part due to longstanding policies promoting very small "kei-cars". In addition, a high proportion of new cars sold are hybrid electric vehicles – 20% in 2019. As a result of these trends, the rated fuel economy of new light-duty vehicles sold in Japan has continued to improve.

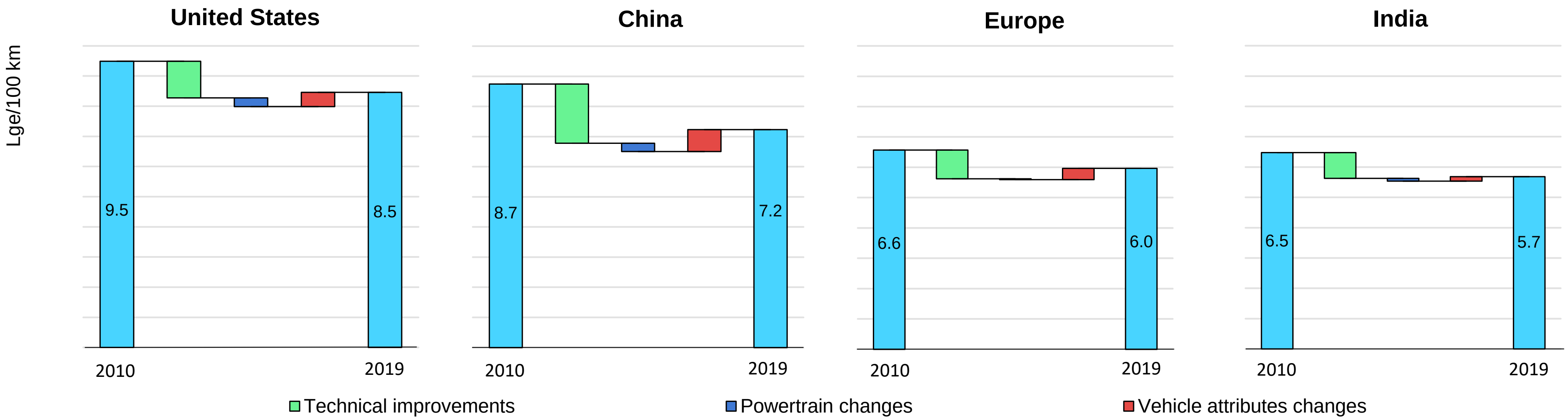
Increasing vehicle size and power has eroded as much as 40% of the fuel consumption improvements that would otherwise have occurred thanks to technical advances in vehicles and engines. Even if vehicles had not grown in size and power, however, the world would still not be on track to meet the GFEI targets, as technical improvements to conventional engines are not sufficient and their progress is slowing.

Alternative powertrains can deliver strong emissions reductions

Hybrid electric vehicles deliver on average about one-third lower fuel consumption than conventional gasoline internal combustion engine vehicles and offer a cost-effective option to considerably improve fuel economy of conventional vehicles. Battery electric vehicles achieve efficiencies two to four times higher than internal combustion engine vehicles, with zero tailpipe CO_2 or pollutant emissions. The energy and fuel efficiency of plug-in hybrids are intermediate, and depend critically on drivers' charging and driving patterns. In 2019, only small shares of the light-duty vehicle market had been claimed by hybrid (3%), plug-in hybrid (1%) and battery electric vehicles (1%), so they had little impact on overall emissions performance. But this is likely to change over the current decade.

Increasing vehicle weight and power have eroded up to 40% of improvements in fuel economy

Decomposition of fuel consumption trends, 2010-2019



Note: Technical improvements refer to the decrease of fuel consumption in each powertrain, excluding the effect of changing vehicle weight and power. (The powertrain comprises the engine, transmission, driveshafts, differential and axles.) Powertrain changes refer to the impact on fuel economy due to changing sales shares of powertrains. Vehicle attributes refer to the change in fuel consumption due to changing vehicle attributes (weight and power). The decomposition methodology is taken from Craglia and Cullen (2019). Europe includes France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit database.

Battery electric vehicles had the lowest global average greenhouse gas emissions across all light-duty vehicle segments in 2019 and in 2030 projections

Integrating well-to-wheel greenhouse gas emissions

Comparing the greenhouse gas emissions impacts of vehicles across different fuel-powertrain options requires looking beyond their rated tailpipe CO_2 emissions. A coherent and complete comparison requires analysing the emissions incurred across the entire life cycle, and includes both the "fuel-cycle" or "well-to-wheel" emissions (those incurred in supplying fuels and in vehicle operations), and "vehicle-cycle" emissions – those incurred in manufacturing vehicles and disposing of them at the end of their life (including recycling).

In extending the analytical scope to a well-to-wheel basis, this report is a first step in extending the scope of the GFEI benchmarking analysis to include the emissions associated with producing, transporting and delivering transport fuels to vehicles.[1]

Key insights from extending the scope to well-to-wheels

The analysis shows that compared with the potential to reduce the carbon intensity of electricity, there is limited scope for reducing the well-to-tank emissions incurred in supplying oil products and natural gas. Moreover, the well-to-tank portion accounts for only 14% to 18% of total well-to-wheel greenhouse gas emissions of conventional internal combustion engine vehicles.

By contrast, for battery electric and fuel cell electric vehicles, emissions incurred in producing and delivering electricity and hydrogen constitute all operational (well-to-wheel) emissions. Rapid deployment of renewables and other low-carbon power generation and hydrogen production technologies are the foundation for decarbonisation across the energy sector (and not only for zero-tailpipe-emission light-duty vehicles). In all regions and in all scenarios, the tank-to-wheel emissions of electricity decrease by 2030. Global tank-to-wheel emissions from supplying electricity decline by 2030 from the 2019 level by more than 25% in the Stated

[1] Previous IEA publications, including the Global EV Outlook 2019 and The Role of Critical Minerals in Clean Energy Transitions, compare the greenhouse gas emissions incurred by different light-duty vehicle powertrains on a full life-cycle basis. The analysis upon which this report builds integrates the well-to-tank greenhouse gas emissions incurred in providing current and future transport fuels into the IEA Mobility Model. Emissions incurred at each step along the fuel supply chain are estimated using IEA databases and modelling tools, as well as the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) tool developed by Argonne National Laboratory. Variability in well-to-tank greenhouse gas emissions across regions and technologies, as well as projections of how these develop in IEA scenarios, were developed for current and future potential road transport fuels.

Policies Scenario, 35% in the Announced Pledges Scenario and 75% in the Net Zero Emissions by 2050 Scenario.

Specific well-to-wheel greenhouse gas emissions, estimated in grammes of CO_2 equivalent per kilometre (g CO_2-eq/km) for each fuel-powertrain combination over the fleet average lifetime, vary considerably across vehicle segments and regions, as well as by scenario.

Emissions performance varies most widely in conventional gasoline and diesel internal combustion engine vehicles, reflecting the range of models and sizes sold in different markets.

For vehicles sold in 2019, a clear rank order in terms of global average well-to-wheel greenhouse gas emissions performance is evident in the Stated Policies Scenario. Battery electric vehicles have the lowest emissions, followed by plug-in hybrids and hydrogen fuel cell electric vehicles. Hybrid vehicles have the lowest well-to-wheel emissions among compressed natural gas, diesel and gasoline internal combustion engines.

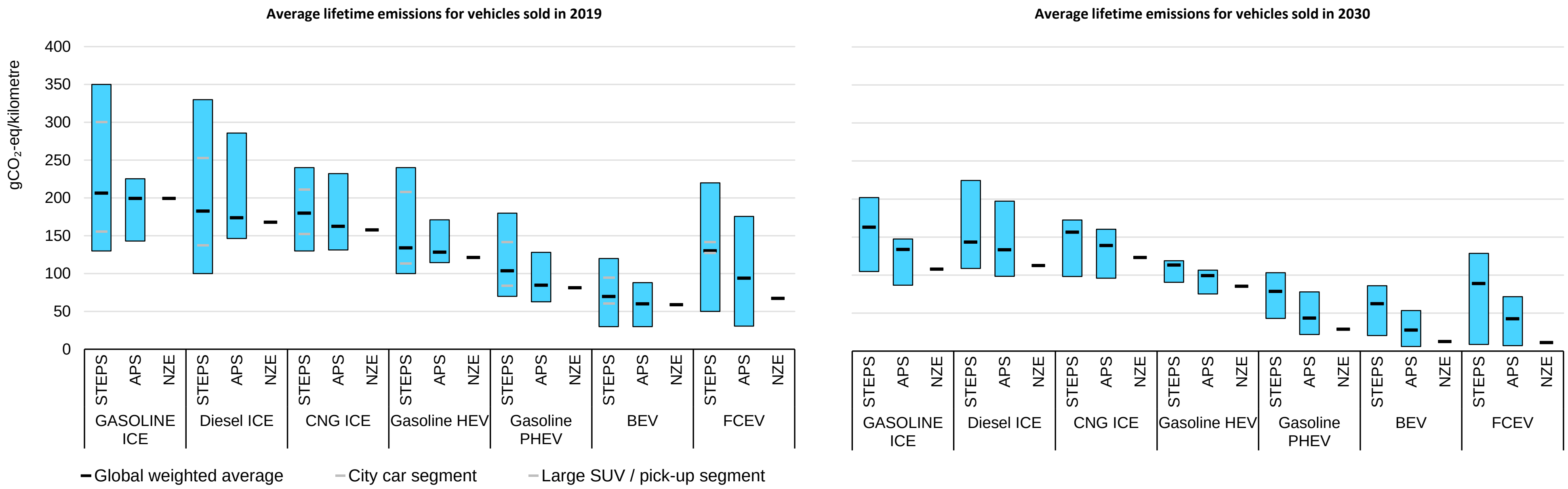
This rank order does not hold across all regions and all scenarios. In the Stated Policies Scenario, hybrid vehicles can emit less than battery electric vehicles sold in 2019 in those regions in which the electricity mix relies particularly heavily on coal, although this is set to change as governments continue to adopt additional policies to decarbonise the power sector as a means to meet their long-term decarbonisation targets.

This is reflected by the Announced Pledges Scenario, in which battery electric vehicles offer the deepest carbon reductions on a well-to-wheel basis in every instance, thanks to rapid reductions in the carbon intensity of electricity generation. The clear coupling between power sector decarbonisation and battery electric vehicles provides a strong rationale for promoting battery electric vehicles as a technology for decarbonising light-duty vehicle operations to meet climate ambitions.

The well-to-wheel greenhouse gas emissions of fuel cell electric vehicles vary depending mainly on how hydrogen is produced. Currently, well-to-wheel emissions of fuel cell vehicles driving on hydrogen produced via coal gasification can be as high as those of gasoline internal combustion engine vehicles, while those using hydrogen from natural gas steam methane reformation achieve well-to-wheel greenhouse gas emissions on par with hybrid electric vehicles. By 2030 in the Announced Pledges Scenario, as more and more hydrogen is produced through electrolysers powered at least in part via renewables, fuel cell vehicles in some regions can also offer near-zero well-to-wheel emissions.

Average rated fuel economy performance and well-to-tank carbon intensity of supplying fuels determine well-to-wheel greenhouse gas emissions intensity

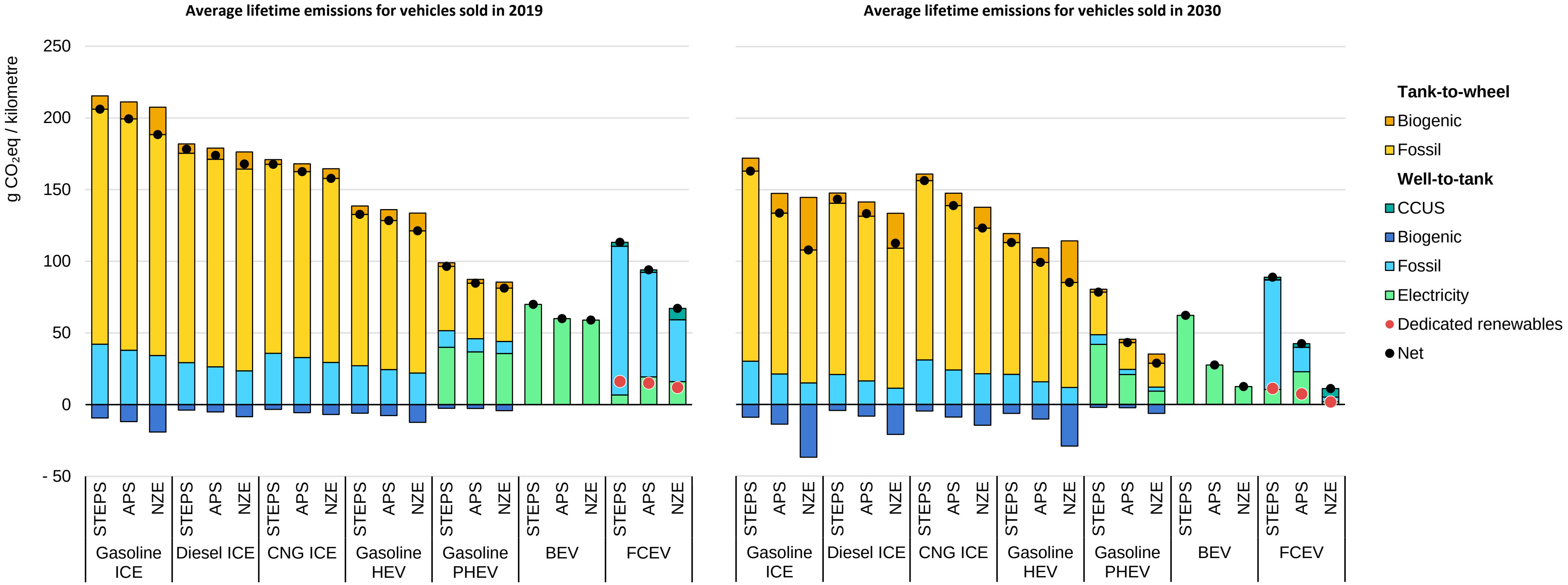
Well-to-wheel greenhouse gas emissions ranges across regions and countries in the Stated Policies Scenario and Announced Pledges Scenario



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; ICE = internal combustion engine; CNG = compressed natural gas; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. Black bars show the global weighted average well-to-wheel greenhouse gas emissions performance. Coloured columns show the range of performance across all five regions covered in detail in this report (China, Europe, the United States, Japan, and developing and emerging countries). Grey bars (2019 STEPS only) show the global weighted average performance of each powertrain in the city car segment (lower bars) and large SUV segment (upper bars), respectively (except for CNG ICE vehicles and FCEVs, where bars show minimum and maximum values across all segments sold).
Source: IEA Mobility Model, September 2021 version.

Battery electric vehicles have the lowest well-to-wheel emissions in all segments

Rated well-to-wheel greenhouse gas emissions of new light-duty vehicle sales worldwide by size segment



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. CCUS = carbon capture utilisation and storage. For FCEVs, the red dots show the well-to-wheel greenhouse gas emissions incurred if hydrogen were to be produced via electrolysis with dedicated renewable sources. The height of the stacked column shows instead total well-to-wheel emissions of fuel cell electric vehicles considering current and projected share of hydrogen production pathways. Therefore, the difference between the red column and the total indicates the theoretical well-to-wheel greenhouse gas emissions reduction potential of FCEVs. The carbon intensity of global electricity generation improves 26% between 2019 and 2030 STEPS and a further 30% between 2030 APS and 2030 STEPS. The utility factor of PHEVs is assumed to improve by six percentage points between 2019 and 2030 STEPS and by a further nine percentage points between 2030 STEPS and 2030 APS. 2019 STEPS considers a vehicle sold in 2019 with well-to-tank intensities evolving in line with the STEPS trajectory, while 2030 APS considers a vehicle sold in 2030 with the well-to-tank intensities evolving in line with the APS trajectories.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

Ten recommendations to align light-duty vehicle efficiency and greenhouse gas emissions with climate goals

Scale up fuel economy standards and electrification targets to support announced net zero emissions ambitions. Market diffusion of vehicle efficiency technologies needs to nearly triple its pace to align operational greenhouse gas emissions of light-duty vehicles with climate pledges. Standards are needed to promote efficiency technologies in conventional internal combustion engine vehicles, and sales share targets for zero-emission vehicles. While separate standards and zero-emission vehicles sales targets can reinforce each other, linking the two in a single regulation carries the risk of creating a regulatory loophole: zero-emission vehicle sales generate compliance credits, relaxing fuel economy standards for a manufacturer's remaining fleet. This loophole can be closed by phasing out multiple credits for zero-emission vehicles as electric vehicle shares grow.

Phase out fuel subsidies and tax road fuels at levels that reflect their impacts on people's health and the climate. Fuel taxes provide consumers with incentives to buy fuel-efficient vehicles and improve the market prospects for conventional hybrids and zero-emission vehicles. Subsidies that reduce the costs of supplying oil and gas products to the road sector should be phased out, with careful consideration of social implications in view of the impacts on poorer parts of the population. Road fuels should be taxed at levels reflecting their impacts on people's health and the climate.

Ensure that regulations are based on and translate to real-world performance. Continued monitoring of the gap between rated and real-world performance is needed to ensure that fuel economy standards have their intended impact. Digital technologies can lower costs and increase effectiveness of compliance monitoring, which should then inform future regulations.

Implement policies to counter the growth in vehicle weight and power. Governments can draw upon existing policies in countries such as France, Japan and Norway, where vehicles sold have consistently been among the lightest and most fuel-efficient worldwide. In addition to high fuel taxes and standards for CO_2 emissions and fuel economy, these countries subsidise and/or tax vehicles according to their weight, size, or greenhouse gas and pollutant emissions, or a combination of these attributes.

Harness the potential of zero-emission vehicles. Zero-emission vehicles, and in particular battery electric vehicles, are the most efficient, cost-effective and sensible technology options for achieving deep reductions in well-to-wheel greenhouse gas emissions in the light-duty vehicles sector. A broad suite of policies targeting vehicle manufacturers can accelerate the market adoption of zero-emission vehicles and ensure that they contribute their full potential to reducing emissions.

Policies promoting plug-in hybrid electric vehicles need to encourage charging and driving patterns that realise these vehicles' full potential to reduce greenhouse gas and pollutant emissions. Trip-making and charging patterns can have a substantial impact on real-world plug-in hybrid fuel economy and electricity, resulting in wide variability between rated and real-world performance. The key to ensuring that plug-in hybrids are driven on electricity will be to tie regulations and incentives more closely to real-world performance.

Harmonise standards beyond the national level. International co-operation and harmonisation of standards can lower the costs of implementing and enforcing regulations such as fuel economy standards. They also provide a valuable basis for engagement to achieve broader societal and environmental goals, including climate goals.

Ensure that emerging markets and developing economies do not become internal combustion engine vehicle dumping grounds. In general, developed countries have put in place the most ambitious fuel economy standards and zero-emission vehicles adoption targets. International co-operation, monitoring of used vehicle trade flows and regulation are needed to ensure that developing and emerging countries do not become dumping grounds for less-efficient internal combustion engine vehicles.

Design a portfolio of policies to reduce emissions throughout the vehicle life cycle. While well-to-wheel and life-cycle analysis can inform broad strategies for decarbonising the transport sector (including in light-duty vehicles), specific policy instruments can best target improvements specific to each of the many regulated industries involved in the fuels and vehicles supply chains. Designing and enforcing separate but in some cases mutually reinforcing regulatory and fiscal instruments for different stages of the life cycle is the most promising means to achieving the rapid action needed.

Promote the adoption of low-carbon fuels, especially direct electrification. Reducing the emissions from generating electricity and producing hydrogen is the foundation of decarbonising the energy sector, and of ensuring that zero-emission vehicles perform to their full potential. Different policies are appropriate to integrate renewables and decarbonise electricity, depending on the current status and mix of electricity generation and energy storage. Within the scope of fuel supply, policies that promote fuels with lower well-to-tank carbon intensity, such as low-carbon fuel standards, are gaining recognition as a policy instrument of choice.

Introduction

The GFEI: Accelerating improvements in vehicle efficiency and electrification

The Global Fuel Economy Initiative, or GFEI, was founded in 2009 to promote and support government action to improve energy efficiency of the global light-duty vehicle fleet. Ever since, the initiative has highlighted the numerous benefits of cost-effective investments in improving fuel economy, including fuel and money savings and reductions in CO_2 emissions. The initiative draws on the expertise of six partners: the International Energy Agency (IEA), the United Nations Environment Programme, the International Transport Forum, the International Council on Clean Transportation, the University of California, Davis, and the FIA Foundation. The initiative pursues three core activities:

- providing data and research analysis of fuel economy potential by country and region
- supporting national and regional policy makers
- raising awareness among stakeholders (e.g. vehicle manufacturers) through outreach and campaigns.

To mark its tenth anniversary in 2019, the initiative relaunched itself by shifting its focus and expanding its scope. Specifically, the initiative:

- Broadened its scope from light-duty vehicles to focus on all road vehicles, setting new targets for vehicle efficiency and electrification within each of four vehicle categories (two- and three-wheelers, passenger light-duty vehicles, heavy-duty trucks, and buses).
- Reaffirmed its mandate to contribute to decarbonising road transport at a pace that complies with goals in the Paris Agreement on climate change.
- Emphasised the criticality of accelerating the transition to zero-emission vehicles, as these have the best prospects for achieving deep decarbonisation goals.

The new targets foreground the potential of zero-emissions vehicles to contribute to emissions reductions. Reducing the emissions incurred when producing and delivering fuels – and ultimately the energy carriers that will power zero-emissions vehicles, electricity and hydrogen – are critical steps in achieving this potential.

Goals of this report

This report presents the latest update to the Global Fuel Economy Initiative's biannual benchmarking report on light-duty vehicle sales. The report provides the latest insights based on a rich dataset covering about 85-90% of global light-duty vehicle sales, extending from 2005 to 2019. To inform the initiative's renewed focus, this report extends the scope of analysis from rated fuel economy and tailpipe emissions to consider emissions incurred in producing, transporting and delivering fuels and energy carriers such as electricity and hydrogen. The report considers the current and potential performance of different light-duty vehicle fuel-powertrain options on a well-to-wheel basis.

Outline of the report

This report focuses on trends in new light-duty vehicles, a category defined as passenger cars and passenger light trucks (collectively, passenger light-duty vehicles), and light-commercial vehicles below 3.5 tonnes.[1] These vehicles account for nearly half of the total well-to-wheel emissions of the transport sector as a whole.

Chapter 1 begins with a policy update, outlining the major developments in fuel economy and CO_2 emissions standards across the world's four largest light-duty vehicle markets since the previous report in 2019. It then updates the status of light-duty vehicle sales in 2019 and 2020, highlighting major trends in where vehicles are sold, and the average rated fuel economy and emissions of these vehicles.

Chapter 2 explores the factors that influence rated light-duty vehicle fuel economy and tailpipe ("tank-to-wheel") CO_2 emissions. By analysing the relationships among fuel economy and technical parameters, it explains the trends and regional variability in the key attributes that determine fuel economy and emissions. It concludes with key policies needed to ensure that emissions of light-duty vehicles are sold in line with climate targets.

Chapter 3 outlines the technologies and processes needed to produce, transport and deliver transport fuels to the vehicle. It explains how emissions are incurred at each step along the fuel supply chain, and explores the variability in "well-to-tank" emissions across regions and technologies and over time.

Chapter 4 describes the different trajectories of operational (also called "well-to-wheel" or "fuel-cycle") emissions of different powertrains, as well as the impact of the gap between rated CO_2 emissions and estimated real-world well-to-wheel emissions. It concludes by comparing the operational emissions incurred by light-duty vehicles sold in major markets in 2019, and those of light-duty vehicles projected to be sold in 2030 in the IEA Stated Policies Scenario and Announced Pledges Scenario.

The report concludes with two annexes. **Annex 1** explains the methodologies used to compile the GFEI dataset. **Annex 2** describes the data sources, assumptions, methodological choices, limitations and potential improvements of the effort to integrate coherent modelling of well-to-wheel emissions into the IEA Mobility Model.

[1] The GFEI database contains model- and, for certain countries, trim-level technology characteristics and sticker prices of new light-duty vehicle sales in 2005, 2008 and 2010-2019, with full data across all years for 21 countries, and partial coverage across an additional 31 countries (i.e. 53 countries in total), See Annex 1 for a list of the countries included in this analysis.

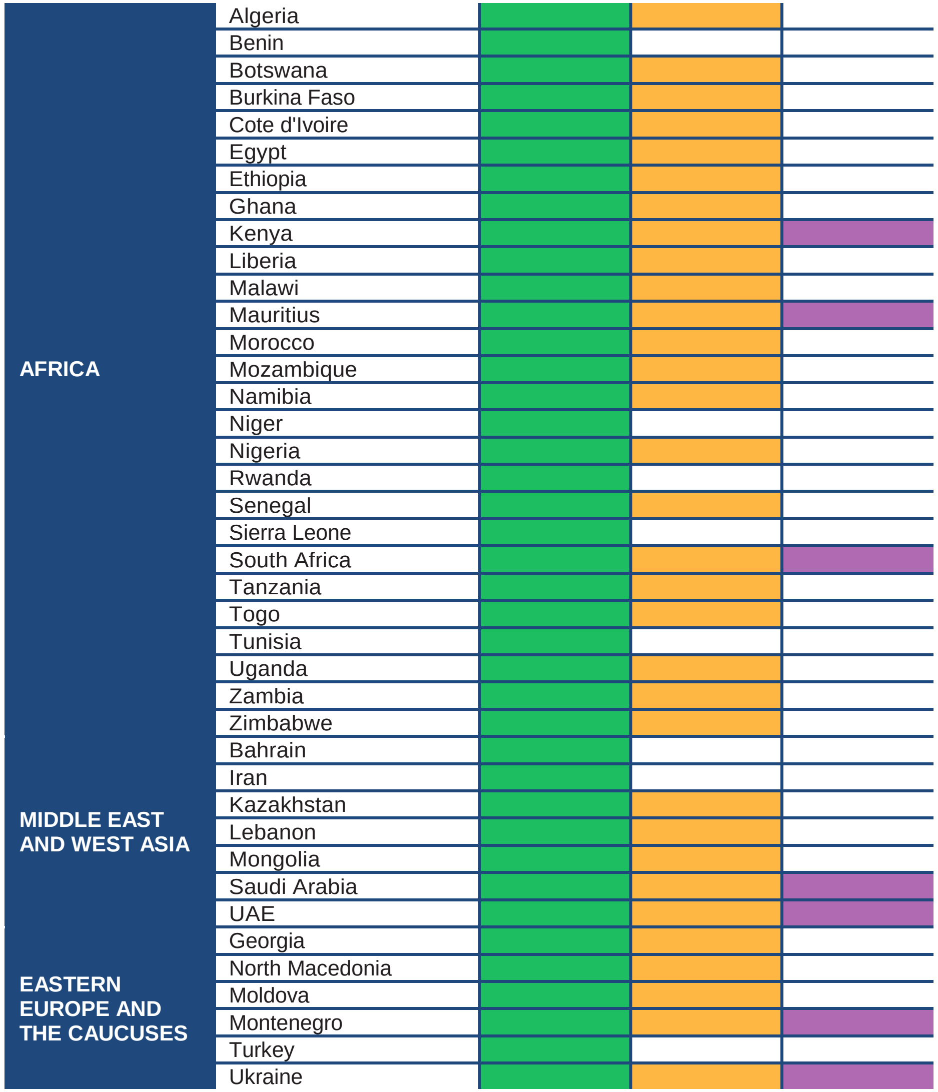
Chapter 1. Trends in the global light-duty vehicle market 2005-2019

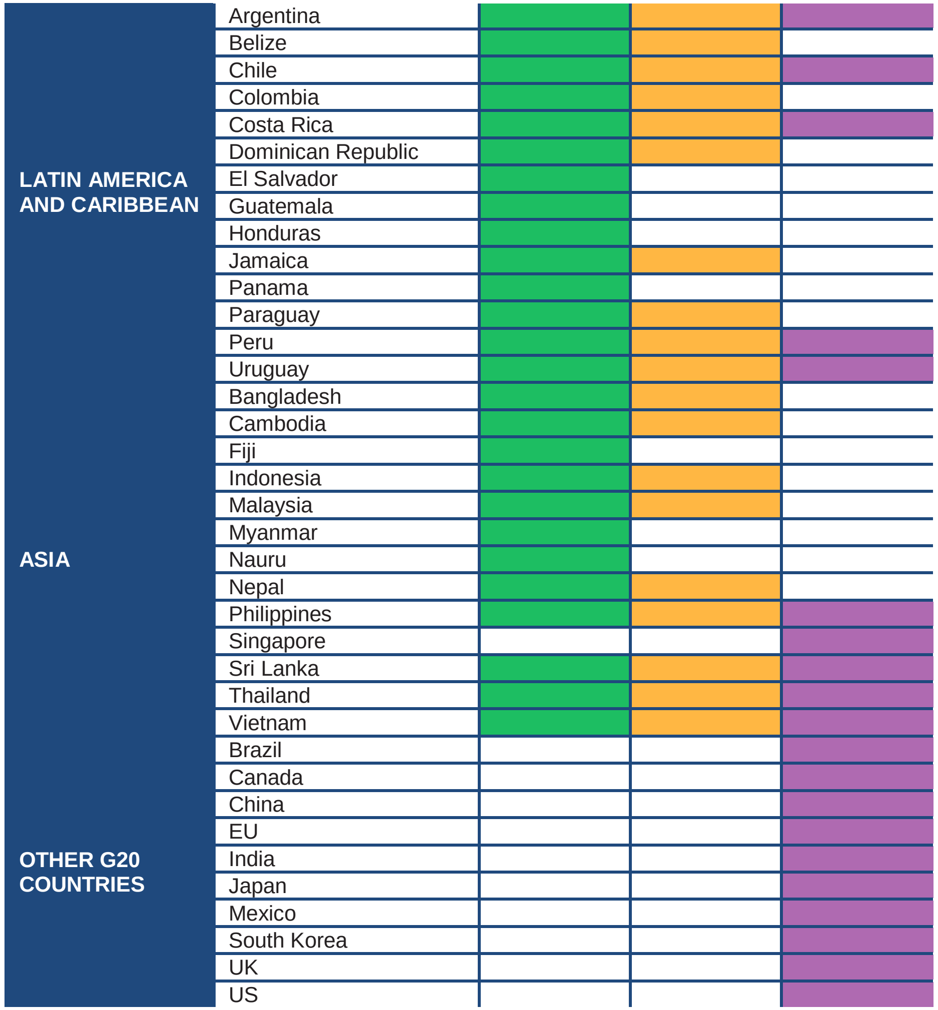
Fuel economy policy in major light-duty vehicle markets

Most new vehicle sales occur in countries with fuel economy standards

Many jurisdictions have reformed fuel economy policy since the last Global Fuel Economy Initiative (GFEI) benchmarking update in 2019. In most major car markets, fuel economy and/or CO_2 emissions regulations have been made more stringent and/or extended. In the United States, the Environmental Protection Agency is re-evaluating fuel economy standards after they were rolled back by the Trump administration. In the European Union, the new CO_2 emissions standards proposed under the Fit for 55 legislative package – supporting its commitment to reduce net greenhouse gas emissions by at least 55% by 2030 – would require that all light-duty vehicles are fully zero-emission vehicles by 2035. In Japan, new vehicles will be tested under the Worldwide Harmonized Light-Duty Vehicle Test Procedure, rather than Japan's own JC-08 test cycle, and the new vehicle efficiency standards are based on well-to-wheel energy efficiency estimates. Finally, several emerging market and developing countries have recently implemented new policies, such as fuel economy labelling and purchase, import, or registration taxes based on fuel or CO_2 emissions performance.

Status of light-duty vehicle fuel economy policies





Notes: GFEI Baseline completed - Policy Implemented - Policy recommendations

Source: Status of GFEI Country Projects, last updated 20 August 2021.

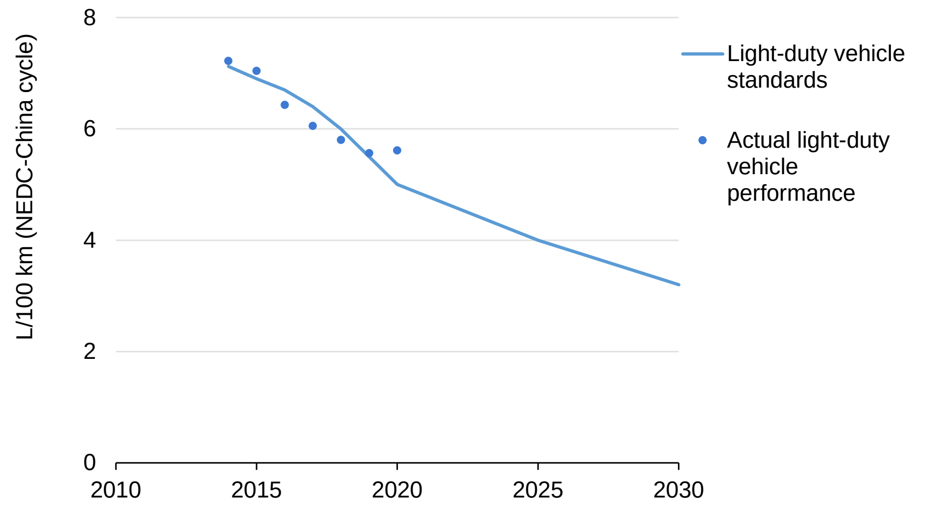
China

The People's Republic of China's (hereafter, "China") corporate average fuel consumption (CAFC) scheme is linked under the "dual credit" scheme to New Energy Vehicle credits. Since 2000, targets under China's CAFC have gradually tightened to reach 5 L/100 km in 2020 (all standards cited here are based on the Chinese version of the New European Driving Cycle [NEDC]). In 2021, China set CAFC targets of 4.0 L/100 km for 2025 and 3.2 L/100 km for 2030. The standards require an annual reduction in specific fuel consumption of 6.5% by 2025 and 5.5% by 2030.

Under the dual credit scheme, in counting a given manufacturer's vehicle production for the CAFC calculation, new energy vehicles are assigned a positive multiplier and effectively counted as multiple vehicles. The new energy vehicle credits (positive multipliers) are applied to the CAFC target, relaxing the stringency of this target.

Regulations define how many new energy vehicle credits each manufacturer must generate each year, with the number of credits increasing linearly from 10% of the manufacturer's vehicle sales in 2019 to 18% in 2023. New energy vehicle credits are generated by selling new energy vehicles, with each generating a different number of credits according to its characteristics. Alternatively, manufacturers running a credit deficit can purchase credits from manufacturers with a credit surplus. At the end of the year, each manufacturer must possess a stipulated number of credits or face strong penalties. Surplus credits can be carried forward by up to three years.

Fuel consumption standards for light-duty vehicles in China



New energy vehicle credits are calculated on the basis of vehicle efficiency, electric range and vehicle weight. For example, a battery electric vehicle with a rated range of 400 km, an efficiency of 23.7 kWh/100 km, and a weight of 2 000 kg would be awarded 2.5 credits. In 2019, a battery electric vehicle was assigned one to six credits depending on its efficiency, range and weight. The credit system thereby provides incentives to innovate in battery, powertrain and vehicle design to improve vehicle efficiency. Since bigger batteries incur more emissions in vehicle production, the policy encourages domestic innovation in batteries but is not necessarily aligned with reducing greenhouse gas emissions on a life-cycle basis in the near term.

From 2021, low-fuel-consumption vehicle categories such as hybrid electric vehicles have been added into the credit scheme. Vehicles with a fuel economy of less than 3.2 Lge/100 km are eligible for these credits. These vehicles do not generate positive new energy vehicle credits but are assigned negative multipliers that decrease the total number of new energy vehicle credits that a manufacturer will be required to produce each year. Their credit multiplier will decline linearly from 0.5 in 2021 to 0.2 in 2023.

The levels of China's subsidies on the purchase of plug-in hybrid and battery electric vehicles will gradually decline and be phased out by 2022. Subsidies favour models with longer driving ranges, better vehicle efficiency and high-density batteries.

China does not have specific zero-emission vehicle policies that reach beyond 2023, when the new energy vehicle credit expires, but has announced clear commitments. Under the New Energy Automobile Industry Plan (2021-2035), 20% of vehicle sales will be new energy vehicles by 2025. The China Society of Automotive Engineers set a goal of over 50% new energy vehicle sales by 2035, which has been endorsed by the State Council.

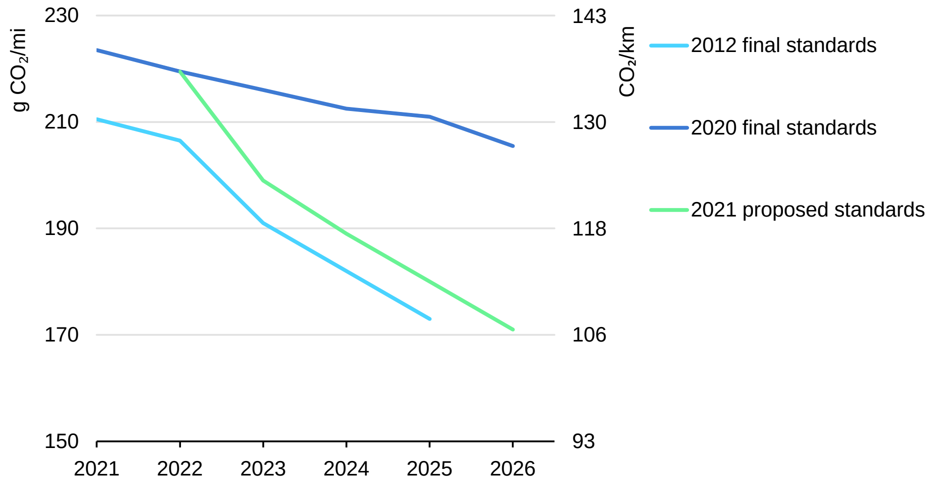
The United States

Under the current Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule, the estimated corporate average fuel economy requirements for cars and trucks combined reach 40.4 miles per gallon, or 202 g CO_2/mile, in model year 2026. The SAFE Rule relaxed the previous standards put in place in 2012, reducing the annual improvement in fuel economy standards from 4.7% in that regulation to 1.5% for model years 2021 through 2026. The rule maintains many of the flexibilities of the previous standards.[1]

In January 2021, the new US administration issued an executive order directing the Environmental Protection Agency to reconsider the SAFE Vehicles Rule and in August 2021 a revision was proposed.[2] The notice of proposed rule-making would establish more stringent standards beginning with model year 2023.

The proposed standards would represent a 10% greater emissions improvement for model year 2023 vehicles than under the SAFE Rule standards and 5% greater emissions improvement each year thereafter. The Environmental Protection Agency is proposing in the new rule to extend the credit multiplier for electric vehicles through model year 2025, while removing the multiplier for natural gas vehicles. The final rule is expected in December 2021. The US government also announced a non-binding goal to reach 50% electric vehicle sales by 2030.

Light-duty vehicle CO_2 compliance targets under 2012, SAFE and proposed rules, in the United States



Notes: Compliance targets based on the corporate average fuel economy test cycle. To enable comparison, the same mix of 50% passenger cars and 50% light trucks was assumed, which differs from the average fleet-wide requirements estimated in the 2012 and 2020 rules.

Sources: EPA (2012), Final Rule, EPA (2020), Final Rule, EPA (2021), Proposed Rulemaking.

[1] These include the credit system, adjustments for air-conditioning improvements, methane and nitrous oxide emissions reductions, and off-cycle technologies. In line with the previous standards, the new rule phased out the greenhouse gas credit multiplier for electric vehicles in model year 2022. However, the multiplier for natural gas vehicles was extended through model year 2026.

[2] The order also directs the agency to "reconsider" the previous administration's withdrawal of California's waiver to enforce emissions standards for cars and light trucks, an exemption that enables several other states to follow California's emissions standards.

The European Union

In the European Union, corporate average CO_2 emissions standards for the period 2015-2019 were set at 130 g CO_2/km (on the NEDC test) for passenger light-duty vehicles and at 175 g CO_2/km for light commercial vehicles. Emissions standards for 2020-2024 were set at 95 g CO_2/km for passenger light-duty vehicles and 147 g CO_2/km for light commercial vehicles. These are the most stringent standards in the world.

In response to the large and growing gap between tested and real-world emissions, the European Union updated its methods for testing fuel consumption and CO_2 emissions. In 2017 it switched to the Worldwide Harmonized Light-Duty Vehicle Test Cycle and Worldwide Harmonized Light-Duty Vehicle Test Procedure, which are designed to better reflect real driving behaviour.[1] During the transition period (2017-2020), vehicles were tested under both procedures and both rated CO_2 emissions values were shown to avoid consumer confusion.

Credits to reward eco-innovation were added to encourage innovative technology – such as LED lights and alternators – that can reduce emissions on the road but not during the test. Credits for eco-innovation were capped at 7 g CO_2/km.

From 2020 onwards, complementary measures for the above regulations take effect. These include a super credit multiplier for vehicles with rated emissions below 50 g CO_2/km, which is gradually phased out through 2022; incentives awarded in cases where the share of zero- and low-emissions vehicles exceeds a determined benchmark; pooling among vehicle manufacturers; and derogation for small volume manufacturers.

Under the super credit, each zero- or low-emissions vehicle is counted as two cars in 2020, 1.67 in 2021 and 1.33 in 2022. This regime is subject to a cap of 7.5 g CO_2/km over the period 2020 to 2022 for each manufacturer.

To meet corporate average CO_2 emissions standards, manufacturers can combine (or pool) their vehicle sales to have all vehicles sold by several manufacturers counted effectively as a single manufacturer. In such cases, super credits and the 7.5 g CO_2/km cap both apply to the pool as a whole.

[1] This is achieved by increasing the maximum tested speed to 132 km/h, adding more aggressive acceleration and deceleration, and shortening idling phases, among other changes. The test mass and road load of vehicles were also updated to better reflect real-world values.

To bridge the gap between real-world fuel economy and values used to calculate rated CO_2 emissions for corporate average compliance, all new vehicles sold from 2021 onwards must come equipped with an on-board fuel consumption meter. Starting in 2022, manufacturers must report annual average fuel (and/or electricity, or hydrogen) consumption to the regulatory agencies. The European Commission aims to use these reported real-world values in future legislation.

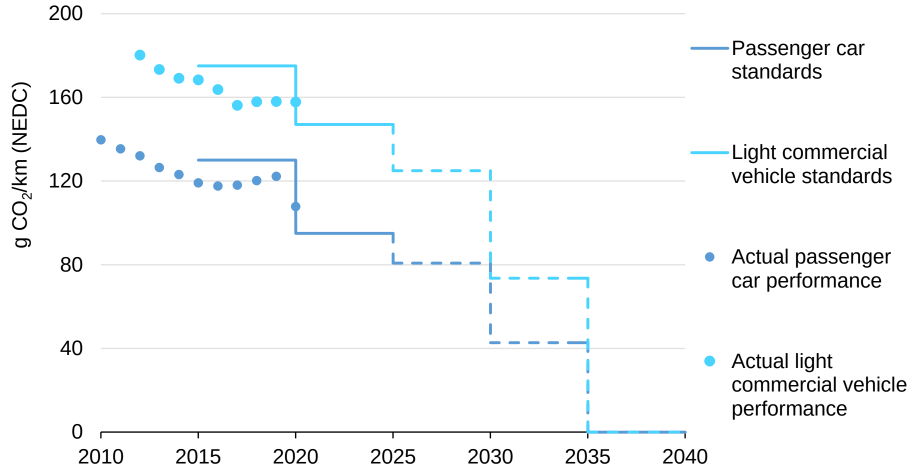
Previous and current EU CO_2 emissions standards for light-duty vehicles

Category	Passenger cars		Light commercial vehicles	
Year/target	Previous	New	Previous	New
2020 (base)	95 g CO_2/km		147 g CO_2/km	
2025	15%	15%	15%	15%
2030	37.5%	55%	31%	50%
2035	--	100%	--	100%

Notes: 2020 emissions are measured with the NEDC. Percentage reductions are benchmarked to the 2020 base year.

Under the Fit for 55 initiative, the European Commission set new CO_2 emissions targets for 2030 onwards, as well as a 2035 target mandating that manufacturers meet zero tailpipe CO_2 emissions. As this effectively mandates that all vehicles sold from 2035 be zero-emission vehicles (and excludes plug-in hybrids, which when running on gasoline will emit CO_2 from the tailpipe), these targets deliver a strong signal to accelerate the transition to zero-emissions vehicles in Europe.

CO_2 emissions standards in the European Union



In 2020, manufacturers had to comply with the stricter CO_2 emissions standards, and the rated CO_2 emissions of passenger cars dropped by 11% (emissions exceeded the 95 g CO_2/km due to flexibilities and zero-emissions vehicle super credits).

This dramatic drop highlights both the effectiveness of standards and manufacturers' response to standards that follow a step function: carmakers will meet standards only in the year in which they are required to do so.

CO_2 emissions standards in the European Union became more stringent in 2020

This report focuses on model-level light-duty vehicle data covering sales from 2005 to 2019 (see Annex 1). However, 2020 was an exceptionally important year for the European light-duty vehicle market since it was the year by which manufacturers had to comply with the new CO_2 emissions intensity target of 95 g CO_2/km. The European Environmental Agency has made available preliminary average CO_2 emissions intensity of the new light-duty vehicles sold in 2020.

The sales-weighted average rated CO_2 emissions of new light-duty vehicles sold in the European Union dropped by an unprecedented 11% between 2019 and 2020, equivalent to the drop between 2010 and 2019. The average CO_2 emissions intensity is above the 95 g CO_2/km target because of the phase-in exceptions and zero-emissions vehicle super credits mentioned above.

Using these preliminary values, we estimate that the annual decrease in fuel consumption between 2005 and 2020 in Europe was 2.0%. This is still lower than the global annual decrease of 2.8% that would have been required from 2005 to meet the 2030 targets of the Global Fuel Economy Initiative (and which would now require annual average decreases of 4.3% to 2030, given that progress has been slower than required).

Despite this, the 11% decrease places the European Union as the region among major light-duty vehicle markets with the fastest decrease in average fuel consumption since 2005. So although 2005-2019 trends show limited fuel economy improvements, a marked change occurred in the European Union in 2020.

Different manufacturers have adopted different compliance strategies to meet the 2020 CO_2 emissions standards. In the light-duty vehicle market, the share of hybrid vehicles doubled from 2019 and the share of electric vehicles tripled.

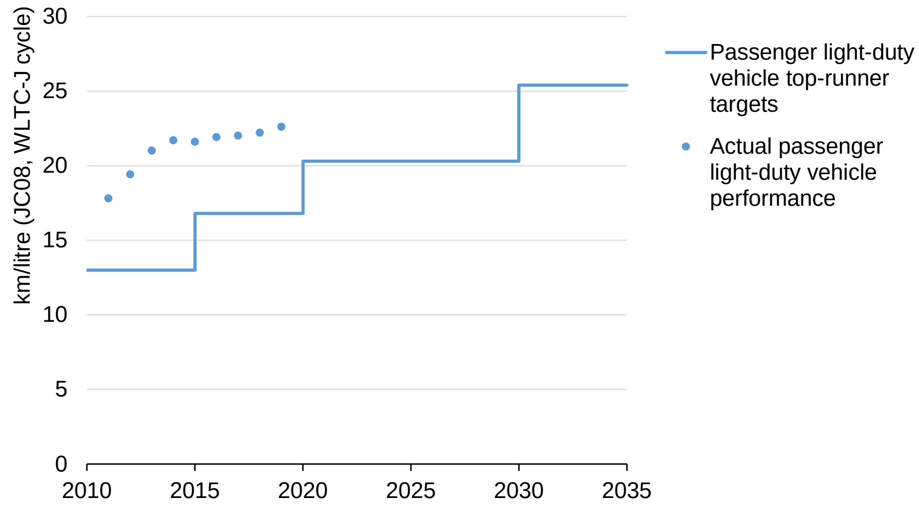
A peculiarity of the EU CO_2 emissions standards is that the targets are set at five-year intervals. Manufacturers have taken advantage of this leeway, which resulted in three consecutive years of increased average emissions intensity in vehicle sales (2017-2019).

Japan

New vehicles sold in Japan lead the world with the lowest sales-weighted specific fuel consumption. Japan determines fuel economy target values for its corporate average fuel economy standards by applying the "top-runner" method. First, the "top runners" are identified: within each vehicle weight category, vehicle type (mini car or standard vehicle) and drivetrain (conventional or hybrid), these are the vehicles with the top 5% of rated fuel economy from a given fiscal year's vehicle sales. Next, an improvement ratio target is set, based on the top runner's fuel economy value.

The target for the 2015 fiscal year specified a 23.5% improvement in fuel economy from 2004 (or a 1.9% annual average reduction). This target did not take hybrid electric vehicles into consideration as a top runner, since hybrids were a novel powertrain at that time. However, with hybrids making up a significant share of new vehicle sales in recent years, they were considered for the 2020 fiscal year target, again using the top-runner approach. The FY2020 improvement ratio was 20% relative to 2015, which, in requiring an annual average reduction of 3.7%, is significantly more stringent than the previous target.

Top-runner fuel economy targets in Japan



Notes: Perfromance and fuel economy targets from 2010-2020 are based on the JC08 test cycle; targets from 2021 onward are based on Japan's Worldwide Harmonized Light-Duty Vehicle Test Cycle (WLTC-J).

Japan has adopted the Worldwide Harmonized Light-Duty Vehicle Test Cycle (WLTC) instead of its own JC08 test cycle from 2021, without revising the 2020 target value (Japan excluded the extra high-speed mode from the worldwide test cycle to adapt it to represent vehicle operations on Japanese roadways). The deviation between JC08 and the worldwide cycle is most pronounced for models with low fuel consumption such as hybrids and kei-cars, as the WLTC has faster acceleration and deceleration cycles, shorter idling durations, and higher shares of the cycle in phases when the engine is warming up, and uses a higher vehicle test mass.

The 2030 targets will have two major differences from the previous policy framework. First, electric vehicles – both battery-powered and plug-in hybrids – will be included for the first time, as this technology is considered sufficiently mature (unlike fuel cell electric vehicles, which will still be excluded). Second, Japan's 2030 target is based on well-to-wheel efficiency, not emissions, thus incorporating well-to-tank energy losses incurred in extracting and converting transport fuels and energy carriers.

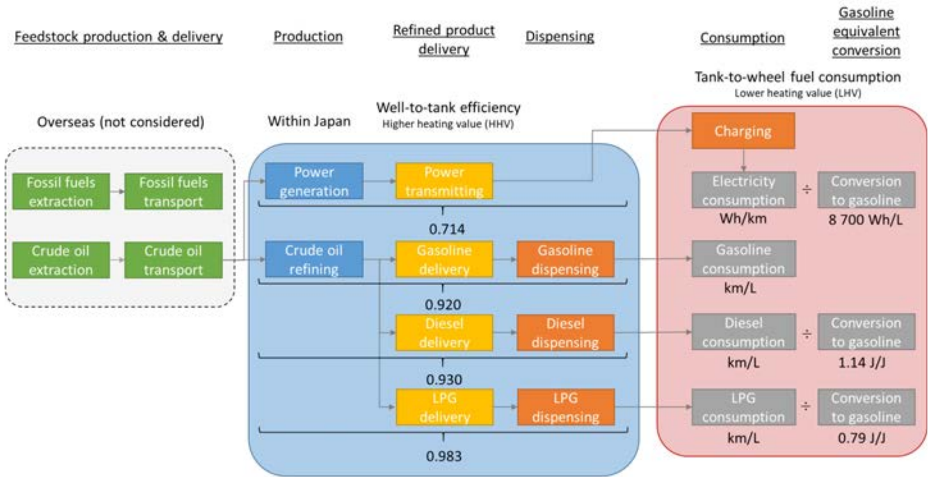
In practice, including well-to-wheel energy losses means that for each manufacturer, the rated tank-to-wheel fuel consumption values will be scaled by a factor according to the efficiency losses associated with producing and provisioning fuel used in that vehicle.

For the purposes of the legislation, gasoline and diesel efficiency are calculated from the point at which domestic operations begin (i.e. refining of crude oil imports), and the efficiency from this stage to the vehicle tank is calculated to be 92%. For electricity, the losses associated with producing, transmitting, distributing and charging are calculated to be 71.4%. This factor is a function of the fuel mix and efficiency of Japan's power generation system. Currently these factors are calculated based on Japan's targeted 2030 power generation mix. According to Japan's first intended nationally determined contribution to the Paris Agreement climate goals, this target mix is: 22-24% renewables, 20-22% nuclear, 27% liquefied natural gas (LNG), 26% coal and 3% oil-based electricity generation.

Given Japan's increased decarbonisation ambition, the 2030 generation mix might be different from the one that has been used to determine these factors. This could mean that the well-to-wheel factors might not be coherent with the power mix that will be in place by 2030.

The new target is expected to stimulate uptake especially of hybrid models, as well as plug-in hybrids and battery electric vehicles. In contrast, fuel cell electric vehicles have hardly penetrated the market, and thus are not included in the 2030 target.

Well-to-wheel energy efficiency standards in Japan



Note: LPG = liquefied petroleum gas.
Source: METI (2019), Fuel Efficiency Standards for Passenger Vehicles in FY2030 Formulated.

Vehicle sales and developments in rated fuel economy

Total light-duty vehicle sales have been decreasing since 2017

In 2019, according to the International Organisation of Motor Vehicle Manufacturers (Organisation Internationale des Constructeurs d'Automobiles [OICA]), combined global sales of light-duty and heavy-duty road vehicles totalled 90 million, down from a peak of 95 million in 2017 (see Annex 1). The Global Fuel Economy Initiative light-duty vehicles sales database underpinning the analysis in this report, based on IHS Markit data, includes 78 million light-duty vehicle sales in 2019, or about 85-90% of the total vehicle sales (light-duty and heavy-duty) reported by OICA. All data presented in this chapter are based on the Global Fuel Economy Initiative database. The largest markets are China (25%), the European Union (18%) and the United States (18%). Sales trends have been markedly different in mature markets and emerging markets.

From 2005 to the 2017 peak

Light-duty vehicle sales volumes in developed markets such as Canada, the European Union, Japan, the United Kingdom and the United States have remained stable since 2005. In 2020, sales dropped because of the Covid-19 pandemic. In these saturated markets, vehicle ownership rates have remained constant for 20 years, declining in certain countries.

In emerging countries, market dynamics have been very different. From 2005 to “peak car” in 2017, emerging markets accounted for the majority of growth in global light-duty vehicle sales. In 2005, emerging market and developing countries had very low vehicle ownership rates (less than or around 1 vehicle per 10 residents), but since then car sales have been increasing as vehicle ownership moves towards levels in developed countries.

This trend is true for most emerging market and developing countries, but is particularly pronounced in China. Light-duty vehicle sales in China grew from under 4 million in 2005 to 26 million in 2017, accounting for two-thirds of the global growth in light-duty vehicle sales.

From peak to present

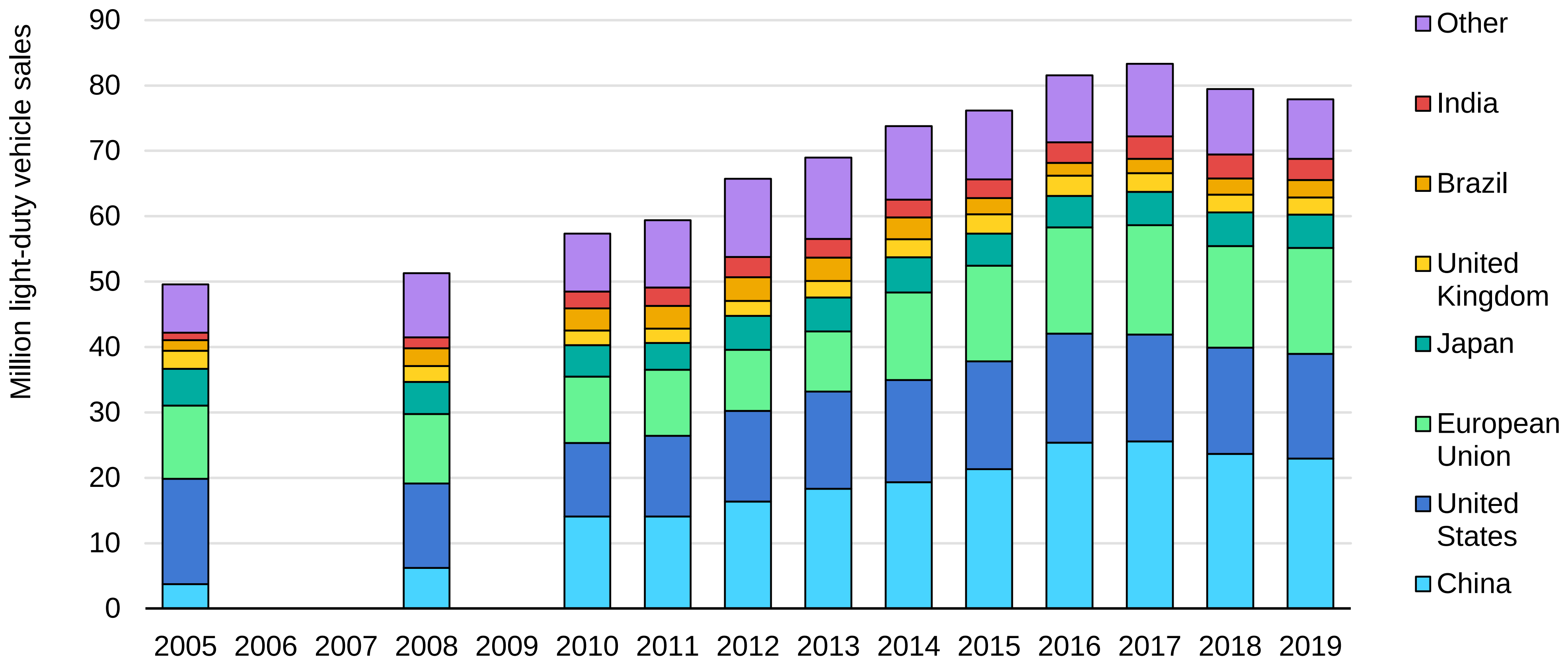
From 2017 to 2019, worldwide vehicle sales decreased by 7%. China played a large role in this trend, accounting for 50% of the decrease. Other emerging market and developing countries accounted for another 35% of the drop, while developed countries accounted for the remaining 15%. Vehicle sales fell in China because of several factors, including car purchase and circulation restriction policies in many large cities, a slowdown in economic growth, the rise of ride-hailing services, and government policy that promotes public transport.

The Covid-19 pandemic resulted in global car sales falling by roughly 15% year-on-year in 2020. The blow has been felt across the globe, but not with equal intensity: sales fell by more than 20% in the European Union, by 15% in the United States, and by only 4% in China.

In the first half of 2021, the global car market recovered from the depths of 2020, but sales are still below 2019 levels. It is possible that 2017 will remain the highest year of sales on record for the next few years.

Worldwide sales of light-duty vehicles peaked in 2017

Global sales of light-duty vehicles by country, 2005-2019



Notes: Light-duty vehicles comprise both passenger light-duty vehicles, or cars, and light-commercial vehicles. Based on the Global Fuel Economy Initiative dataset, which covers 86% of the total vehicle market as estimated by OICA.

Source: IEA analysis based on IHS Markit database.

Mapping average fuel consumption in 2019

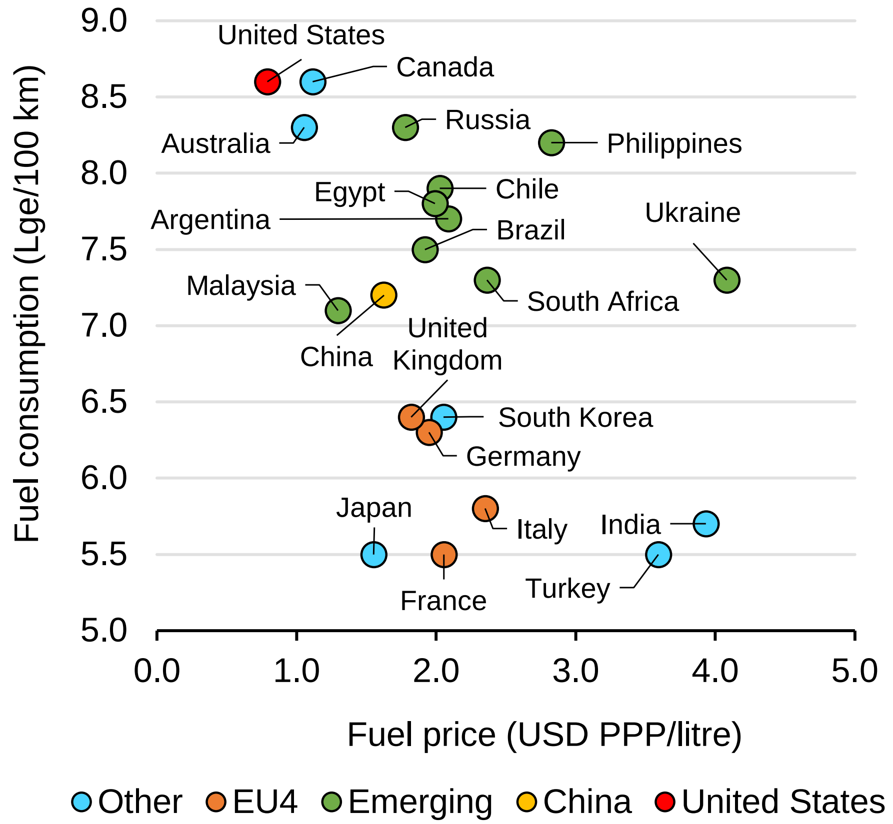
The rated specific fuel consumption of new light-duty vehicles sold in 2019 was 7.1 Lge/100 km) and ranged from 5.5 Lge/100 km in Japan to 8.6 Lge/100 km in Canada. When converted to tailpipe (tank-to-wheel) CO_2 emissions, the average was 165 g CO_2/100 km, and values ranged from 126 g CO_2/100 km in Japan to 198 g CO_2/100 km in Canada.

Countries with lower fuel consumption (below 6 Lge/100 km) are mostly European countries, developed Asian economies and India. Most emerging market and developing countries are in the middle of the spectrum (6-8 Lge/100 km), and at the higher end (above 8 Lge/100 km) are developed countries in North America.

Fuel taxation, regulations and GDP per capita

A useful way to map differences in fuel consumption of new vehicles is to examine how patterns in fuel consumption vary across countries with different fuel prices and GDP per capita.

Rated light-duty vehicle fuel consumption versus gasoline prices in 2019



Notes: EU4 = France, Germany, Italy and the United Kingdom; Russia = Russian Federation. Fuel price is scaled by the price level ratio using PPP conversion factors to reflect the affordability of gasoline in each country.

Sources: IEA fuel price data; OECD and World Bank PPP conversion factors; IEA analysis based on IHS Markit database.

Higher fuel prices are correlated with lower fuel consumption, as one would expect. Since oil products are a globally traded commodity, the cost of producing automotive-grade gasoline or diesel varies little across regions. Most of the variability in fuel prices can be explained by fuel taxation and subsidy regimes.

European countries, Japan and Korea tend to apply high fuel taxes, which push fuel prices above USD 1.5/litre (scaled to reflect affordability using PPP). The sales-weighted average fuel consumption of light-duty vehicles sold in many of these countries are among the lowest in the world. In these countries, fuel economy regulations are also stringent.

In contrast, fuel taxes in Australia, Canada and the United States are low, fuel prices are just below USD 1/litre, and the average fuel consumption of light-duty vehicles is above the global average.

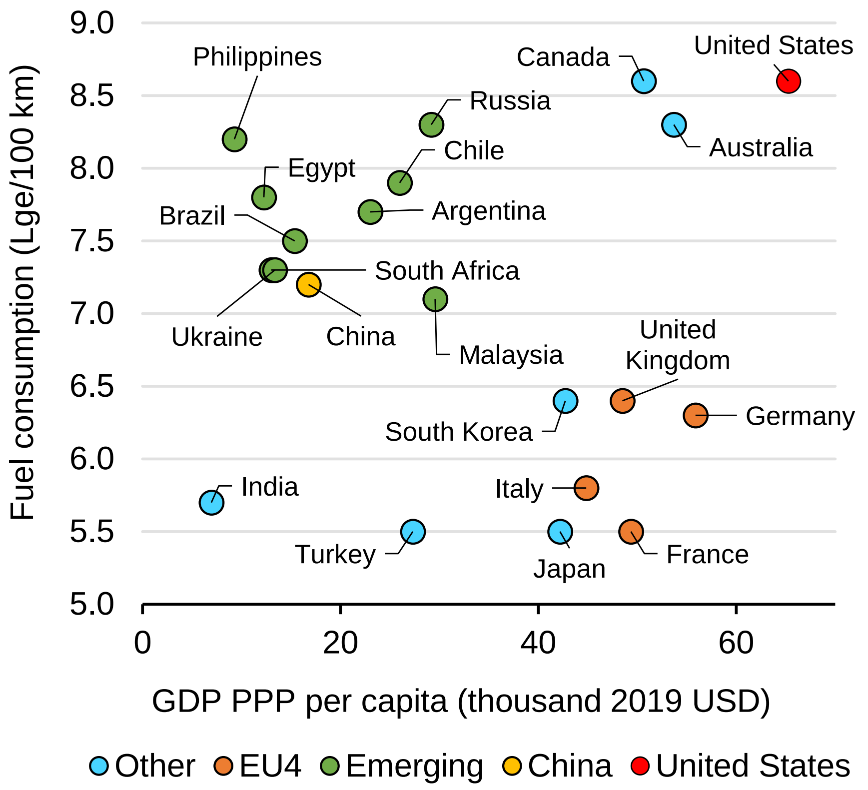
In developed countries where GDP per capita is higher, fuel consumption tends to be higher too, and vehicles are generally larger and less efficient. For emerging and developing countries the trend is not clear.

When scaled to adjust for purchasing power, fuel prices in emerging market and developing countries are similar to those in Europe and Japan. Although these countries have lower GDP per capita, rated average fuel consumption of new vehicles lies between the values in North America and those in Europe. This is because fuel economy policies are absent or lax, and vehicle buyers may be less willing to pay for fuel-saving technologies. In unregulated markets, manufacturers have less incentive to build and sell their most efficient vehicle models, equipped with the latest efficiency technologies.

Policy implications

Countries with stable regimes of higher fuel taxes – and hence higher prices – generally have lower average fuel consumption. So removing fuel subsidies and gradually increasing fuel taxes to reflect the health and climate impacts of fuel use should be considered important policy levers to push down fuel consumption.

Rated fuel consumption versus GDP PPP per capita



Notes: Fuel price is scaled by the price level ratio using PPP conversion factors to reflect the affordability of gasoline in each country.
Source: IEA analysis based on IHS Markit database.

Country classification used in this report

Discussion on fuel consumption and CO_2 trends in the remainder of this chapter, as well as in Chapters 2 and 4, focuses on four countries and groupings:

- China.
- The United States, which serves as an archetype for Australia and Canada, which also have high GDP, low fuel prices and high fuel consumption.
- The European Union, referred to in the text as Europe. In Chapters 1 and 2, figures and discussion on Europe focus only the four largest European markets – France, Germany, Italy and the United Kingdom – referred to as EU4. In Chapters 3 and 4, figures and discussion refer to the entire European Union.
- Emerging market and developing economies: countries with low GDP and high fuel consumption, including Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, the Russian Federation and Ukraine.

Fuel consumption improvements have stalled

The average fuel consumption of new light-duty vehicles – standardised to the Worldwide Harmonized Light-Duty Vehicle Test Cycle and measured in litres of gasoline equivalent per 100 km (to enable comparison across fuels) – has been decreasing on average by 1.6% per year since 2005. The pace of decrease has been slowing since 2015, however. Between 2017 and 2019, the trend came almost to a halt, decreasing by only 0.4% per year.

In the United States, fuel consumption decreased rapidly between 2005 and 2015, by 2.5% per year, due to corporate average fuel economy standards and increasing oil prices. The reduction has slowed down since. Between 2017 and 2019, fuel economy changed little.

In the European Union, fuel consumption fell rapidly from 2005 to 2015 mostly because of higher diesel sales shares and mandatory CO_2 emissions standards. After 2015 the rate of improvement in Europe also stalled, and between 2017 and 2019 specific fuel consumption increased by 2.8%.

In China and in emerging countries, fuel economy improved between 2005 and 2015 at only half the rate observed in developed countries. Average vehicles in these markets became larger, and fuel efficiency technologies that were common in developed countries (such as turbochargers, lightweighting and gasoline direct injection) had not yet become standard in new light-duty vehicles. In the last four years, fuel consumption in China decreased by 2.7% per year, thus becoming the main contributor to global improvements in fuel economy. This can be attributed to stringent fuel standards and the adoption of electric vehicles. On the other hand, the fuel economy of light-duty vehicles sold in emerging markets did not significantly improve between 2017 and 2019.

When the Global Fuel Economy Initiative targets were first benchmarked to 2005 global fuel economy, the average yearly reduction in fuel consumption needed to halve fuel consumption by 2030 at a global level from 2005 to 2030 was pegged at 2.8%. Because of slow progress to date, from 2019 onwards the average fuel consumption of new cars sold each year would need to decline 4.3% per year, faster than in any single year observed in the data.

Trends in CO_2 emissions

Without significant adoption of vehicles with alternative fuels (especially zero-emissions vehicles), CO_2 emissions follow fuel consumption trends closely. This was largely the case from 2005 and 2017. However, since 2018, electric vehicles have started to make up more than 1% of sales, and thus the two trends have begun to diverge slightly: when running on electricity, battery and plug-in electric vehicles do not consume fuels and generate no CO_2 emissions from the tailpipe (on a tank-to-wheel basis).

Because zero-emissions vehicles emit no CO_2, between 2017 and 2019 rated average tailpipe CO_2 emissions of global light-duty vehicle sales decreased 1.6% while fuel consumption decreased only 0.9%. This effect is most pronounced in countries with high electric vehicle market penetration, such as China, where average CO_2 emissions dropped by 6.3% between 2017 and 2019, while fuel consumption decreased by 5.3%.

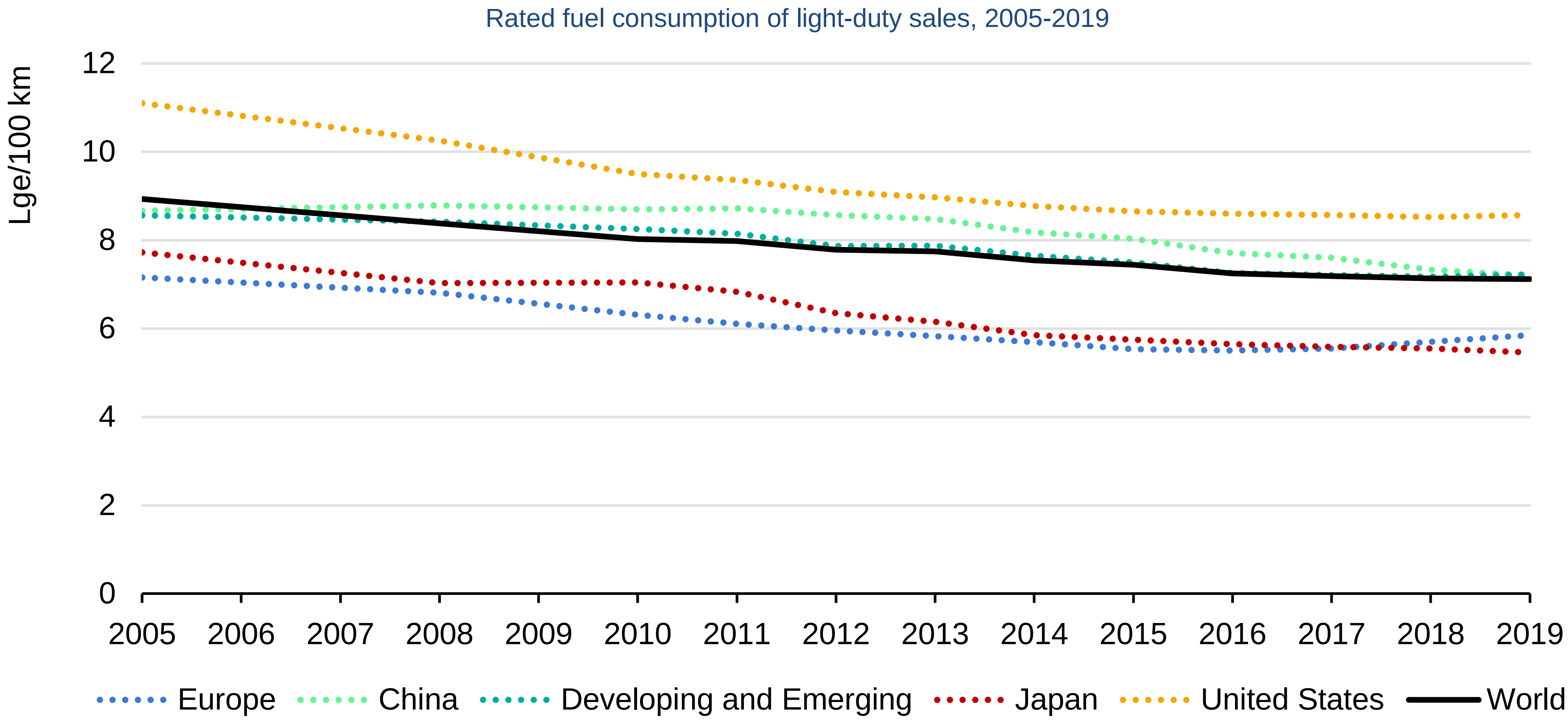
Annual fuel economy improvements need to triple to meet the 2030 targets of the Global Fuel Economy Initiative

Fuel consumption trends by region and the 2030 fuel economy target for light-duty vehicles

	Historical					GFEI target
	2005	**2010**	**2015**	**2017**	**2019**	**2030**
Global						
Fuel consumption (Lge/100 km)	8.9	8.0	7.4	7.2	7.1	4.4
Yearly change		-2.1%	-1.5%	-1.7%	-0.5%	-4.3%
Yearly change since 2005		-2.1%	-1.8%	-1.8%	-1.6%	-2.8%
United States						
Fuel consumption (Lge/100 km)	11.1	9.5	8.7	8.6	8.6	
Yearly change		-3.1%	-1.9%	-0.5%	0.0%	
Yearly change since 2005		-3.1%	-2.5%	-2.1%	-1.8%	
European Union						
Fuel consumption (Lge/100 km)	7.2	6.3	5.5	5.5	5.8	
Yearly change		-2.5%	-2.6%	0.1%	2.7%	
Yearly change since 2005		-2.5%	-2.5%	-2.1%	-1.4%	
China						
Fuel consumption (Lge/100 km)	8.7	8.7	8.0	7.6	7.2	
Yearly change		0.1%	-1.6%	-2.7%	-2.7%	
Yearly change since 2005		0.1%	-0.8%	-1.1%	-1.3%	
Emerging						
Fuel consumption (Lge/100 km)	8.6	8.3	7.5	7.2	7.2	
Yearly change		-0.7%	-1.9%	-1.9%	0.1%	
Yearly change since 2005		-0.7%	-1.3%	-1.4%	-1.2%	
Other						
Fuel consumption (Lge/100 km)	8.2	7.5	6.6	6.4	6.4	
Yearly change		-1.7%	-2.6%	-1.3%	-0.2%	
Yearly change since 2005		-1.7%	-2.2%	-2.0%	-1.8%	

Notes: GFEI = Global Fuel Economy Initiative. All fuel economy values were harmonised to the Worldwide Harmonized Light-Duty Vehicle Test Cycle. The GFEI dataset covers about 85-90% of the total vehicle market.

Rated fuel consumption reduction of new light-duty vehicles is stalling

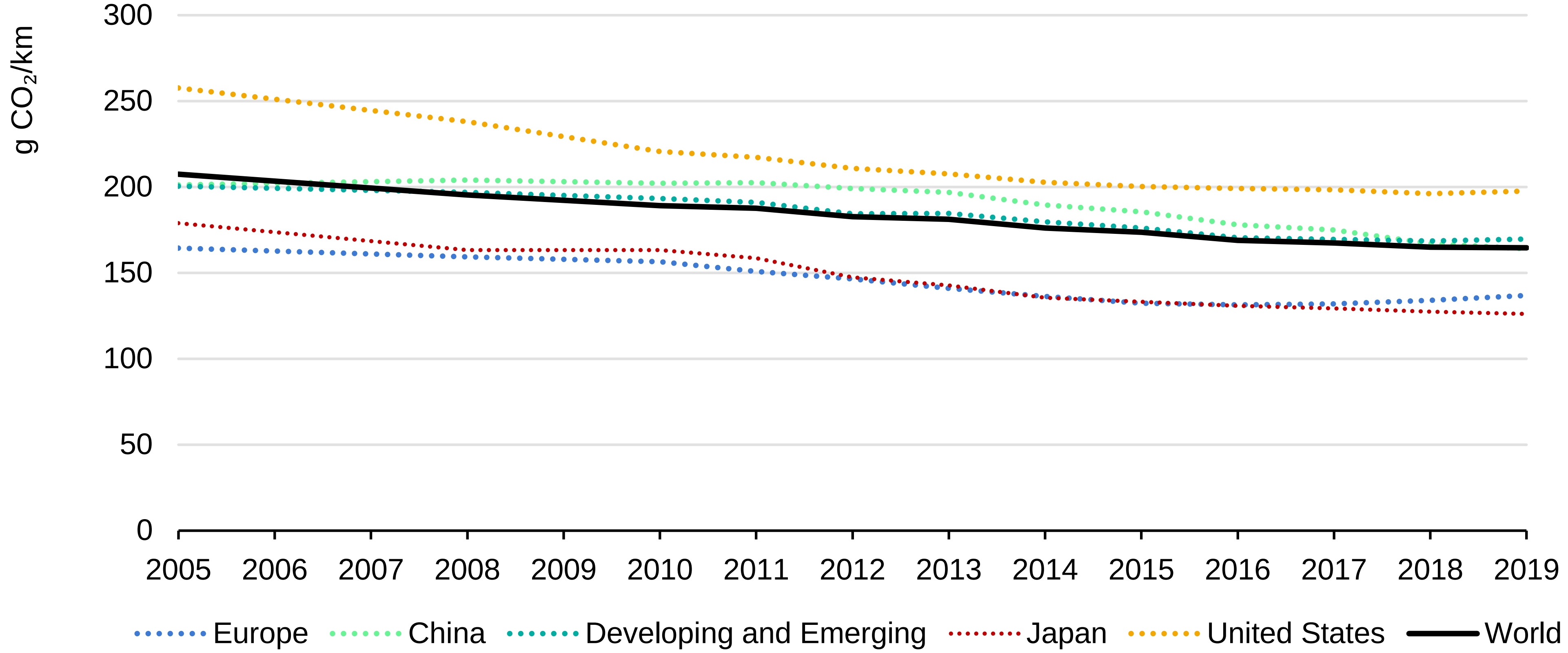


Notes: All fuel economy values were harmonised to the Worldwide Harmonized Light-Duty Vehicle Test Cycle. The Global Fuel Economy Initiative dataset covers about 85-90% of the global vehicle market. EU27 refers to the current member states of the European Union.

Source: IEA analysis based on IHS Markit database.

Rated average CO_2 emissions intensity of light-duty vehicles continue to decline very slowly

Rated CO_2 emissions intensity of new light-duty sales, 2005-2019



Notes: Rated CO_2 emissions were harmonised to the Worldwide Harmonized Light-Duty Vehicle Test Procedure. The Global Fuel Economy Initiative dataset covers about 85-90% of the total global vehicle market.

Source: IEA analysis based on IHS Markit database.

Fuel economy projections

Trends in well-to-wheel greenhouse gas emissions in light-duty vehicles

IEA scenario definitions

The IEA Stated Policies Scenario (STEPS) incorporates the impact of current and stated policies, including fuel economy standards, zero-emission vehicle mandates and regulations that call for a full phase-out of internal combustion engine vehicles. It also includes the impact of policies enacted in legislation that reduce the carbon intensity of fuels supply, such as renewable portfolio standards on electricity, energy system-wide or fuel-specific technology adoption, or CO_2 or greenhouse gas emissions reductions targets.

The Announced Pledges Scenario (APS) assumes that all national climate commitments by governments around the world, including nationally determined contributions to the Paris Agreement and net zero emissions pledges, are realised in full and on time. It therefore goes beyond the policy commitments incorporated in the Stated Policies Scenario. The aim of the Announced Pledges Scenario is to see how far full implementation of national net zero emissions pledges takes the world towards reaching net zero emissions. The case is not designed to achieve specific outcomes and show a pathway to reach them. It is an exploratory scenario that defines a set of starting conditions and then sees where they lead.

The Net Zero by 2050 Scenario (NZE) seeks to model a transition to a net zero energy system by 2050 while ensuring stable and affordable energy supplies, providing universal energy access, and enabling robust economic growth.

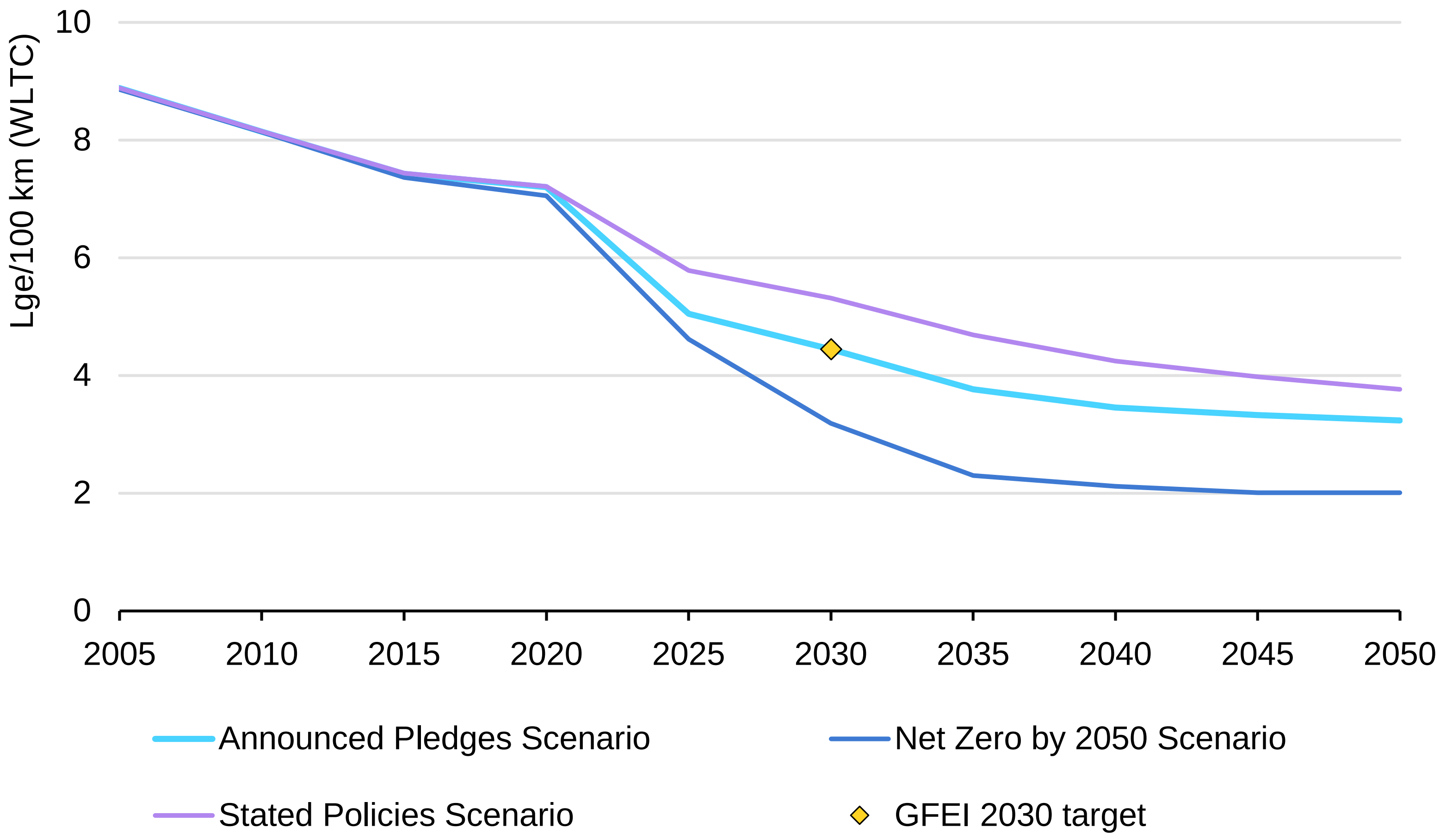
IEA Scenarios and GFEI targets for light-duty vehicles

The Global Fuel Economy Initiative's target for fuel economy is to halve the tank-to-wheel fuel consumption of new light-duty vehicles by 2030 relative to 2005. Comparing the Stated Policies Scenario, the Announced Pledges Scenario and the Net Zero by 2050 Scenario shows that current policies fall short of this near-term target.

Achieving the 2030 Global Fuel Economy Initiative target requires improving internal combustion engine vehicle efficiency, adopting further and more stringent fuel economy policies, and increasing market shares of hybrid electric and zero-emission vehicles.

Full implementation of the IEA Announced Pledges Scenario meets the GFEI 2030 targets for the fuel economy of new light-duty vehicles sales

Global fuel economy improvements in new light-duty vehicle sales, GFEI target and IEA Scenarios, 2005-2050



Note: Rated tank-to-wheel fuel economy normalised globally to the Worldwide Harmonized Light-Duty Vehicle Test Cycle.
Source: IEA Mobility Model (2021 September version).

Fuel economy developments in the IEA Scenarios

Reducing the fuel consumption of new light-duty vehicles, and consequentially their tailpipe CO_2 emissions, is essential to meeting societal goals ranging from improving local air quality to limiting climate change.

Although fuel consumption stopped falling between 2017 and 2019, in the Stated Policies Scenario global fuel consumption decreases on average by 3.2% per year to 2030. The scenario shows that existing and stated fuel economy and zero-emission vehicle policies in the coming decade, plus expected market penetration of efficiency technologies, can improve the rated fuel consumption of light-duty vehicles.

This trajectory yields a global average fuel consumption of 5.1 Lge/100 km – well short of the Global Fuel Economy Initiative target of 4.4 Lge/100 km. Only markets with stringent fuel economy policy and an already efficient vehicle market – the European Union, India, Japan and Korea – attain average fuel consumption below the 4.4 Lge/100 km target. Other regions continue with historical improvement rates of around 2% per year.

In the Announced Pledges Scenario, higher penetration of zero-emission vehicles, wider adoption of fuel economy standards and increased stringency of existing standards push fuel consumption down by 5% per year on average, meeting the Global Fuel Economy Initiative target (4.4 Lge/100 km) to reach global average fuel consumption of 4.2 Lge/100 km. The drop in average fuel consumption is driven by advanced economies and China – markets that reach large market shares of zero-emission vehicles by 2030. Emerging markets and developing economies also speed up progress to improve fuel economy by close to 4% per year – 45% faster than in the Stated Policies Scenario. Most of these improvements come from the adoption of more efficient technologies at the vehicle, powertrain and engine level in conventional internal combustion engine and hybrid electric vehicles.

Improvements in internal combustion engine vehicles

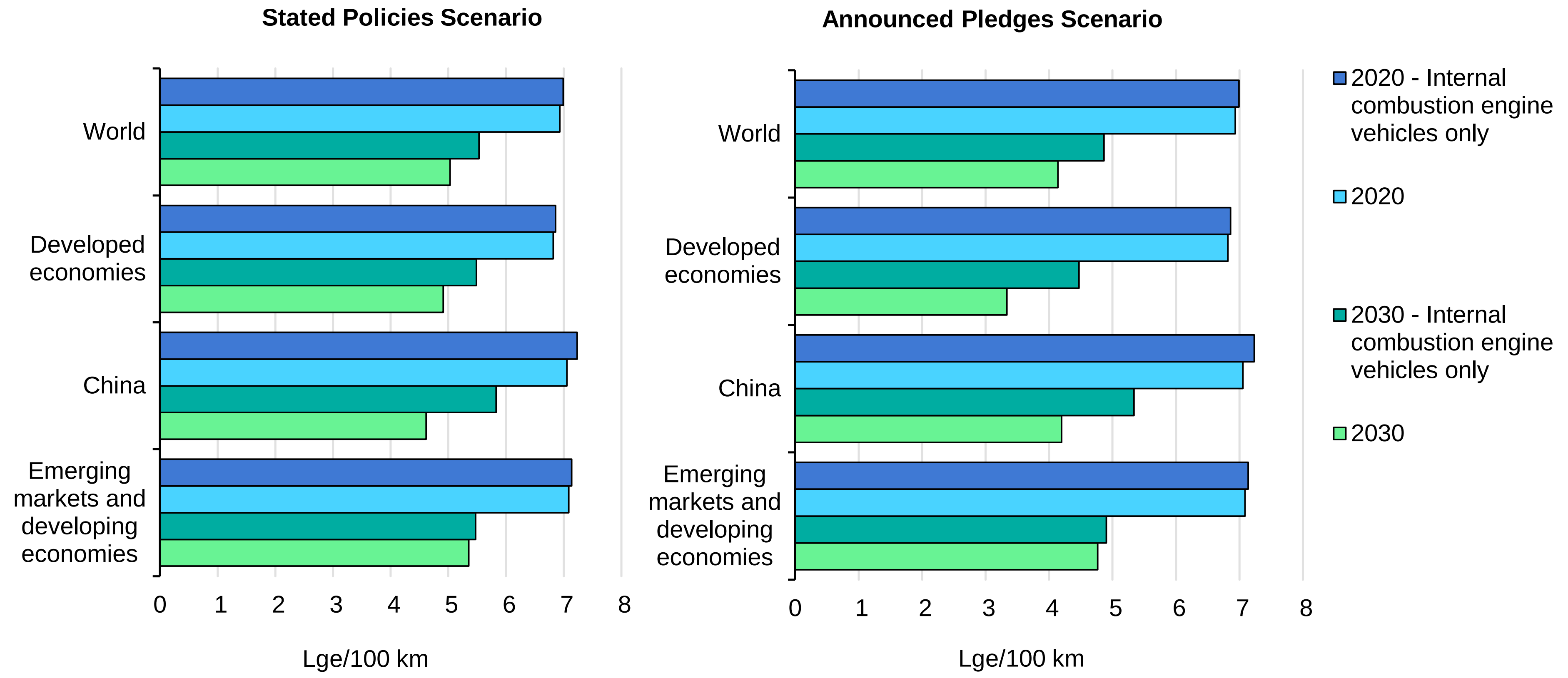
Improving the fuel consumption of internal combustion engine vehicles by deploying engine efficiency technologies, hybrid powertrains and vehicle design improvements such as lightweighting are cost-effective means of decreasing CO_2 emissions. This is especially important in emerging markets and developing economies, where the lack of charging infrastructure and affordability constraints make the adoption of electric vehicles less compelling in the short term.

In the Stated Policies Scenario, the fuel consumption of vehicles powered by internal combustion engines improves by 2.3% per year, twice as fast as the average trend between 2010 and 2019. In the Announced Pledges Scenario, annual average improvements reach 3.6% over the same decade, mostly thanks to an acceleration in China and in emerging markets and developing economies.

There is a risk that given the current focus on electrification, manufacturers will reduce their investments in vehicle efficiency technologies for internal combustion engine vehicles. However, fuel consumption targets cannot be met at a global level unless internal combustion engine vehicles are equipped with efficiency technologies, as meeting the target through market penetration of electric vehicles alone would require far faster penetration of these vehicles than is achieved in the Announced Pledges Scenario. Such a development is likely to be possible only if fuel economy standards are implemented, with sufficient stringency, not only in leading markets but also in many emerging markets and developing economies. Setting such standards is particularly important for emerging markets and developing economies, as internal combustion engine vehicles are expected to retain the majority of light-duty vehicle sales over the coming decade. Standards are also needed to prevent these countries from becoming dumping grounds for used or outdated technologies, and can further provide incentives to manufacturers to continue investing in fuel economy technologies.

Rated fuel consumption needs improving in new internal combustion engine and zero-emission vehicles

Average rated fuel consumption of new vehicles, all sales and internal combustion engine vehicles, in the Stated Policies Scenario and Announced Pledges Scenario, 2020 and 2030



Notes: Internal combustion engine vehicles include hybrid electric vehicles. Rated fuel economy (tank-to-wheel) is harmonised globally to the Worldwide Harmonized Light-Duty Vehicle Test Cycle. Please see Annex for detailed definitions of regions.

Source: IEA Mobility Model (2021 September version).

Deployment of hybrid electric vehicles in emerging markets and developing economies

Hybrid powertrains have been commercially available since 1997. They reduce fuel consumption because they can recover energy from braking and allow the engine to operate at closer to optimal efficiency than conventional (non-hybrid) internal combustion engine vehicles. Currently, hybrids have a 33% lower fuel consumption than gasoline internal combustion engine vehicles in the same segment.

In most emerging markets and developing economies, the electrification of light-duty vehicles presents challenges in the short term for two reasons. First, the purchase price of electric vehicles is higher than that of comparable internal combustion engine vehicles, and is likely to remain so for at least the better part of this decade. In countries where purchasing power is constrained, this can be a very large barrier to adoption. Second, electric vehicle adoption requires a strong, reliable and conveniently accessible electricity grid, and large-scale adoption is likely to require rolling out public charging infrastructure. This presents a challenge even for industrialised countries and is likely to continue to be difficult for many emerging markets and developing economies. While it is important to accelerate the adoption of zero-emission light-duty vehicles in all countries, these short-term challenges cannot serve as a pretext for delaying aggressive fuel economy standards, as the benefits of improved fuel economy must also be shared in emerging markets and developing economies.

Currently, vehicles sold in emerging markets and developing economies tend to have a lower share of fuel-saving technologies: a medium car sold in this regional grouping consumes 14% more than one sold in Europe, while being 130 kg lighter and having 13% lower power. The deployment of existing state-of-the art engine and powertrain technologies in these countries could decrease consumption substantially. A way to rapidly decrease the average fuel consumption in emerging markets and developing economies could be a high adoption of hybrid powertrain technologies.

This would leapfrog more conventional engine efficiency technologies and directly adopt the ICE technology with the lowest consumption.

Chapter 2. What determines fuel economy and tailpipe CO_2 emissions?

Factors that influence fuel consumption

Why have improvements in rated average fuel consumption stalled?

Carmakers are continuously improving vehicle efficiency by adding new fuel-saving technologies, but globally improvements in the fuel consumption and CO_2 emissions of new light-duty vehicles stalled in 2018-2019. To understand why this is the case, it is necessary to look into a few key attributes that influence fuel consumption.

Specific fuel consumption: Useful energy and efficiency

Specific fuel consumption measures the amount of fuel (or electricity) required for a vehicle to move a given distance under a test cycle designed to reflect common driving conditions. The amount of fuel used depends on the useful energy required to move the vehicle and the efficiency with which fuel is converted into mechanical energy provided to the wheels.

The amount of energy needed to move a vehicle is mostly determined by the vehicle's weight and size. The mass of the vehicle is a key determinant of how much energy is needed to accelerate the vehicle, while the frontal area determines how much energy is required to counteract air resistance. Vehicle energy efficiency is also influenced by drag, tyre resistance and the lateral surface of the vehicle.

A vehicle's energy conversion efficiency depends on the performance of the powertrain, which consists of both the engine and the drivetrain. Over more than a century, engineers have made thousands of incremental improvements that increase internal combustion engine efficiency.

Some powertrains are fundamentally more efficient than others: diesel engines are more efficient than gasoline ones, hybrid powertrains are more efficient than conventional internal combustion engines, and electric powertrains are considerably more efficient than any internal combustion engine vehicle.

Vehicle characteristics and consumer choice

Continuously improving vehicle technologies is only one aspect of fuel economy improvements. Weighted-average fuel consumption depends on the mix of vehicles sold, which is determined by consumer choices.

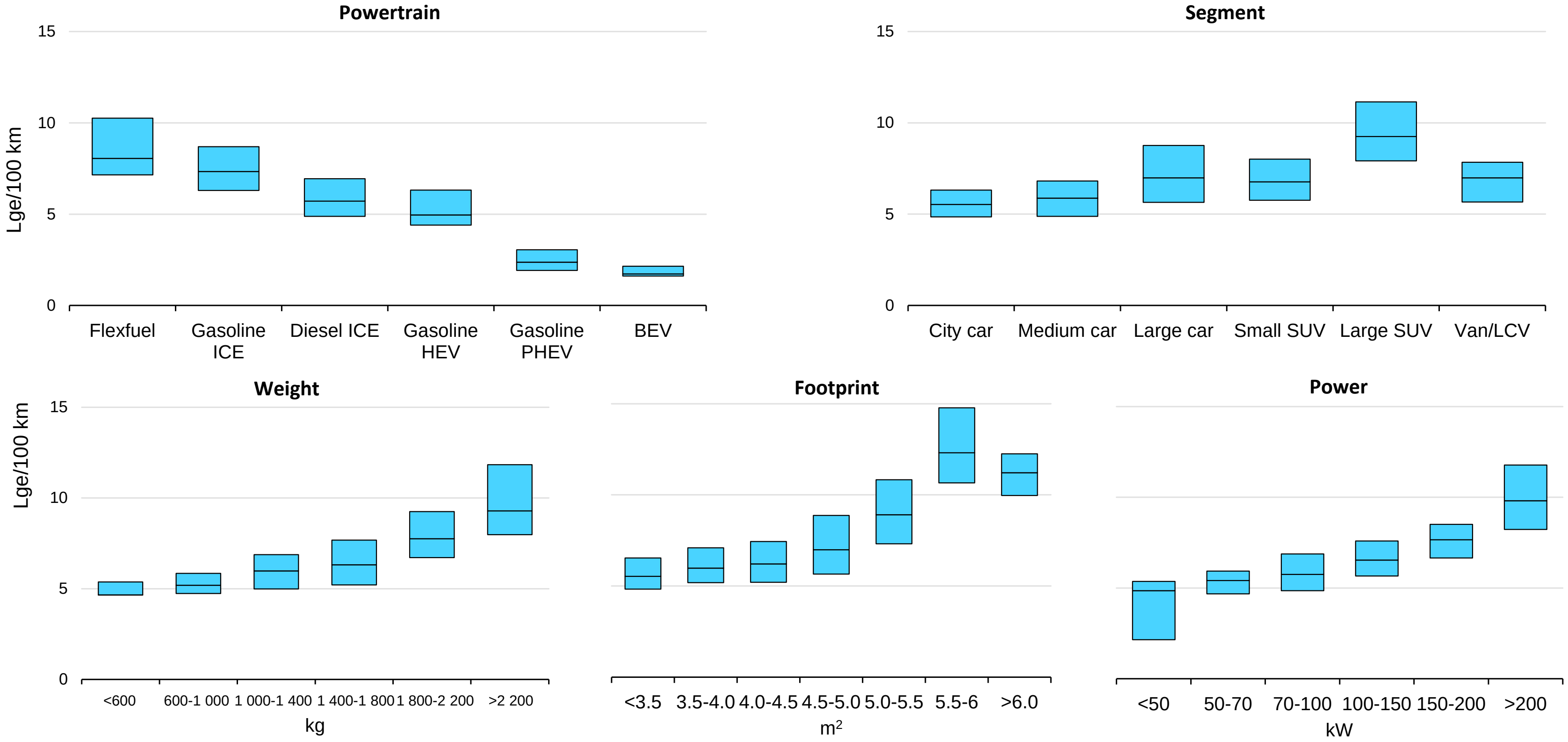
In this chapter we analyse the structure and development of the light-duty vehicle market by tracking six vehicle characteristics and their relation to fuel consumption: size segment, powertrain, power, engine displacement, weight and footprint.

The analysis is performed at a global level and with a focus on major car markets. Particular attention is given to the latest data available (2019), to the progress over the course of the most recent data update (from 2018 to 2019), and finally to the overall evolution between 2005 and 2019 for key regions.

The chapter concludes by examining policies that could provide incentives for consumers to prefer low-emissions powertrains and to buck the recent trend towards ever-larger cars.

Vehicle powertrain, weight, size and power are key determinants of specific fuel consumption

Relationship between specific fuel consumption and key vehicle attributes



Notes: Lge = litres of gasoline equivalent; ICE = internal combustion engine; HEV = hybrid electric vehicle; PHEV = plug-in electric vehicle; BEV = battery electric vehicle; LCV = light commercial vehicle. The lines across the boxes indicate the central 50th percentile across all vehicle models, using the full sample of vehicles in the database. Distributions shown are not weighted by sales volumes. The powertrain is the engine or motor plus the drivetrain. There is no official and harmonised definition of vehicle size segments, but the classification of segments adopted in this study is consistent across years and region. Vehicle kerb weight measures the overall vehicle mass, excluding any passenger or cargo load. Vehicle footprint is the area defined by the vehicle wheelbase and axle width. Vehicle power refers to the rated power of the vehicle engine and/or motor.

Source: IEA analysis based on IHS Markit database.

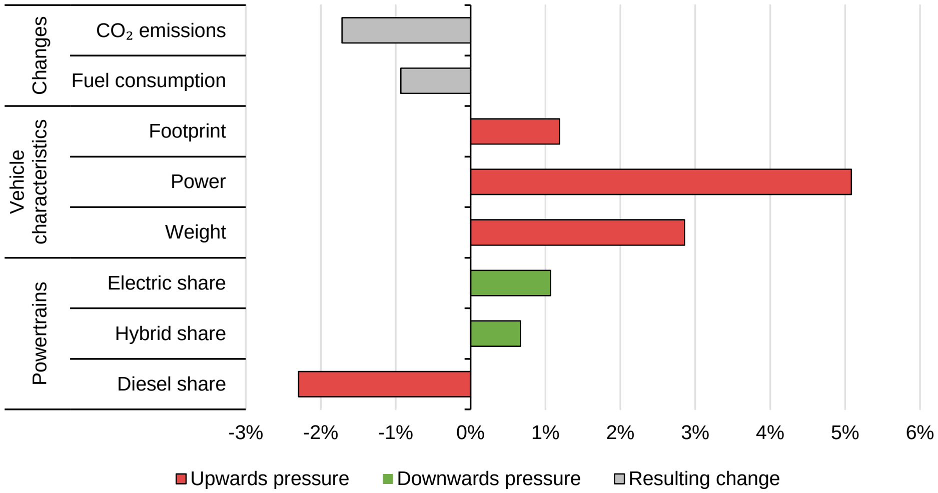
Slow adoption of efficient powertrains and massive uptake of larger, heavier and more powerful vehicles are causing fuel economy improvements to stall

Global average fuel consumption of new vehicles decreased by a mere 0.9% between 2017 and 2019. Two trends have counteracted progress in fuel economy. First, a shift towards larger, heavier and higher-powered vehicles increased average weight by 1.6%, average power by 5% and average footprint by 1%. Second, the sales share of diesel powertrains decreased from 14% to 12%.

At the same time, electric vehicle sales shares increased by 1%, and hybrid electric vehicle shares increased by 0.7%. In Europe, the net effect of heavier, more powerful vehicles and of small increases in hybrid electric vehicle and electric vehicle sales shares was a 5.4% increase in fuel consumption between 2017 and 2019. In the United States, these trends cancelled each other out, resulting in no change in average fuel consumption. By contrast, fuel economy improved by 5.3% in the People's Republic of China (hereafter, "China"). China's share of global light-duty vehicle sales decreased during this period, so the impact of fuel economy improvements in China on global trends is more muted than in previous years.

Achieving the fuel economy targets of the Global Fuel Economy Initiative will require reversing the trends that have blocked further improvements in recent years. Policies can achieve this by accelerating adoption of efficient powertrain technologies and discouraging sales of ever-larger and -heavier vehicles.

Trends affecting global fuel consumption, 2017-2019



Notes: Red columns show trends that lead to higher fuel consumption, and green indicate trends that lead to lower fuel consumption.
Source: IEA analysis based on IHS Markit database.

Since 2010, a large share of efficiency gains have been offset by increased vehicle weight and power

Analysing the impact on fuel consumption of vehicle attributes, changes in the market share of powertrains and technical advances makes it possible to disentangle the impacts of increasing vehicle size and weight from technical efficiency improvements. Such decomposition analysis, using the logarithmic mean Divisia index, also reveals the extent to which larger, heavier vehicles have offset technological progress.

Efficiency technologies have not been adopted fast enough

Efficiency technologies include those at the engine and powertrain level (including in the transmission), as well as enhancements in vehicle design (aerodynamics, lightweighting, and other engineering and materials improvements). The impact of these technical improvements, accounting for vehicle weight, power and powertrain technology, varies among major markets, but in all markets they improved rated fuel consumption between 2010 and 2019. They have had greater impact on fuel consumption than any other factor, including vehicle weight and power (vehicle attributes), or powertrains.

Technical improvements have led to the greatest absolute and relative progress in fuel economy in China, mostly due to the rapid penetration of state-of-the-art engine technologies over the 2010s.

Light-duty vehicles sold in the United States also benefited considerably from uptake of efficiency technologies, including efficient engine technologies and engine downsizing. In Europe, technical advances have been more modest since many engine efficiency technologies already became standard in 2010 to meet CO_2 emissions standards. In addition, adoption of more expensive efficiency technologies was not required in the 2010s, as the standards were relatively lax. India has also experienced only moderate technical progress. Investments in efficiency technology may have been limited by the fact that India's light-duty vehicles tend to be small and therefore have low fuel consumption.

Powertrain shifts

Net changes in the market share of powertrain technologies – both towards and away from more efficient powertrains – have not had a major impact on average fuel consumption in most markets.

In China, the emergence of electric vehicles and hybrids, together with a decrease in the market share of flex-fuel vehicles, whose rated fuel consumption is marginally higher than that of standard gasoline internal combustion engine vehicles, contributed a 0.3 Lge/100 km decrease in average fuel consumption from 2010 to 2019.

In Europe the large decrease in the market share of diesel powertrains, which has led to higher fuel consumption, has been nearly entirely counterbalanced by increases in hybrid and electric powertrains. As a result, shifting market shares of powertrains have had a negligible impact on average fuel consumption.

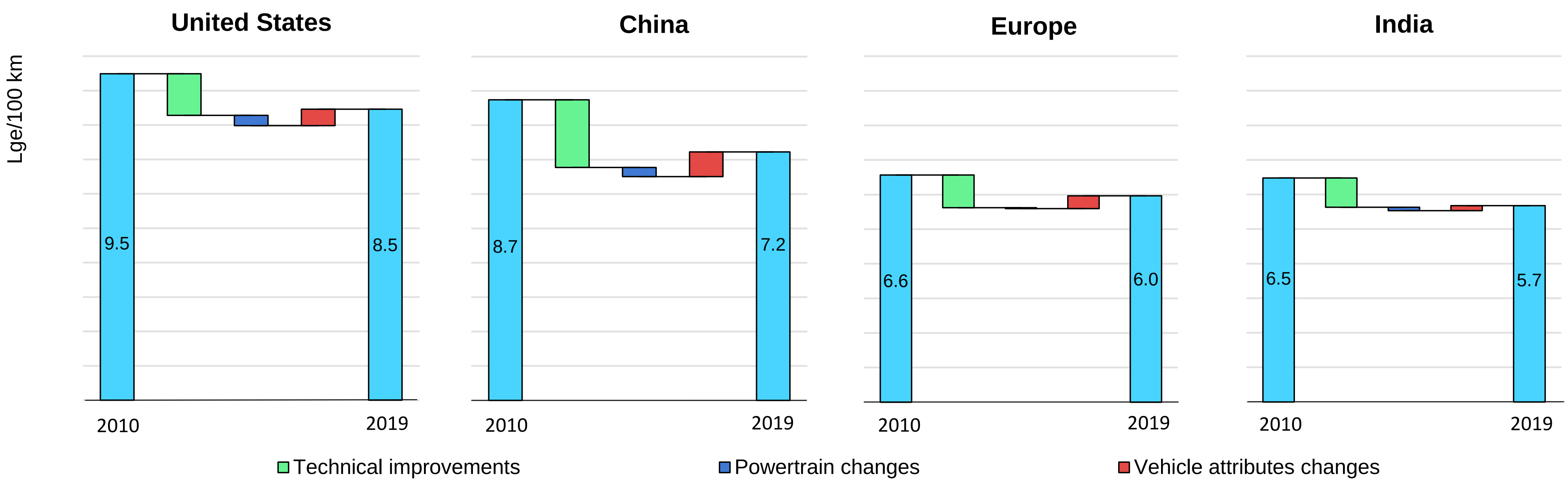
Vehicle attributes counteract fuel savings from technical improvements

In all markets analysed, vehicle weight, power and footprint have all increased, pushing up average fuel consumption. The share of technical improvements that have been nullified by increasing vehicles attributes ranges from nearly 40% in the United States, China and Europe to 17% in India. The impact of increased vehicle size on fuel consumption has been the largest in China, where vehicle weight and power have increased the fastest, albeit from low baseline weight and power levels. By contrast, increased weight, power and footprint have affected average fuel consumption the least in India. This is because average vehicle size and power have changed little, so most technical improvements have translated directly into improved fuel economy.

If vehicles sold in 2019 had the same average weight and power as they did in 2010, the annual improvement in fuel economy would have been 1.7% to 1.9% in Europe, India and the United States. In China, the improvement would have been 3.2% per year. When the Global Fuel Economy Initiative target was set, benchmarking to 2005, the annual improvement required to meet the 2030 target of halving rated fuel consumption was calculated at 3.0%. According to the above analysis, only China would have met this target if vehicle attributes had remained constant over the years. So while increases in vehicle size and power have held back fuel economy improvements, even if vehicle changes had not occurred, the rate of adoption of efficiency technologies and more efficient powertrains still would not have been sufficient to stay on track with the targets of the Global Fuel Economy Initiative.

Increasing vehicle size has offset up to 40% of technical efficiency improvements to fuel economy across four of the world's major light-duty vehicle markets

Decomposition of fuel consumption trends, 2010-2019



Notes: Technical improvements refer to the decrease of fuel consumption in each powertrain, excluding the effect of changing vehicle weight and power. Powertrain changes refer to the impact on fuel economy due to changing sales shares of powertrains. Vehicle attributes refer to the change in fuel consumption due to changing vehicles attributes (weight and power). The decomposition methodology is taken from Craglia and Cullen (2019). Europe includes France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit database.

Rated fuel consumption diverges from real world consumption but is still a useful indicator

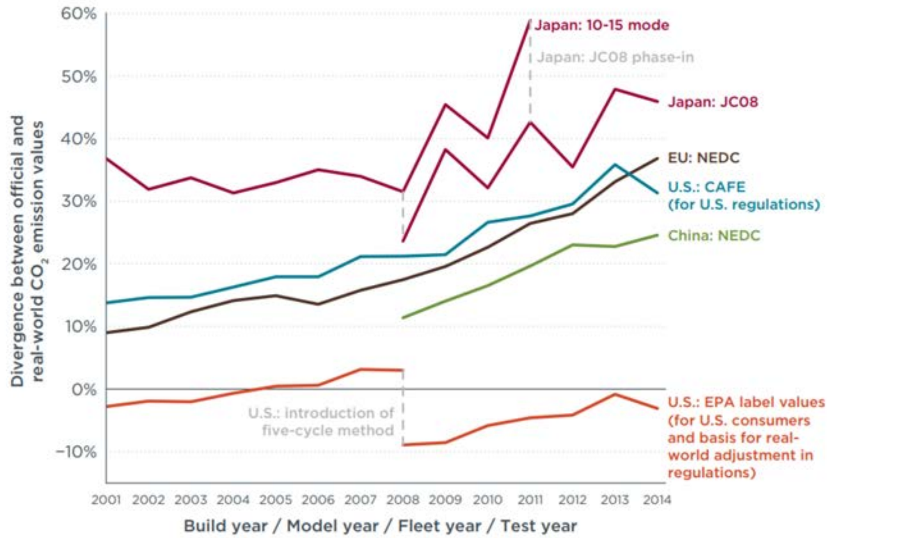
To determine whether vehicles comply with fuel economy standards, official fuel economy or specific fuel consumption ("fuel consumption") or CO_2 emissions per kilometre are measured in controlled conditions. Depending on each country's regulatory requirements, such testing is conducted by a government agency, certified independent laboratories or by manufacturers themselves, with or without supervision from government. Vehicles are placed on dynamometers, allowing them to remain stationary while running, and fuel consumption and emissions are measured.

Despite regulators' efforts to ensure that the rated fuel consumption measured in laboratories reflects real-world driving conditions, real-world and rated fuel consumption differ significantly. Governments need to continue their legislative and regulatory efforts to monitor the gap.

The benchmarking report and targets of the Global Fuel Economy Initiative are based on rated fuel consumption values. Rated fuel consumption is the only metric available for a group of countries across a significant time frame, which is a necessary requirement for global benchmarking and comparisons. In the Global Fuel Economy Initiative dataset, rated fuel consumption was converted from national test cycles to estimated performance on the Worldwide Harmonized Light-Duty Vehicle Test Cycle using the zero-intercept conversion equations developed by the International Council on Clean Transportation.

In addition, rated fuel consumption allows meaningful comparisons because it tends to be similarly divergent from real-world conditions across powertrains. Plug-in hybrid electric vehicles are an exception because their real-world fuel consumption depends strongly on the share of distance they travel in electric mode, which is determined to a large degree by driving and charging behaviour. For battery electric vehicles, the discrepancy is generally higher than for internal combustion engines, especially when auxiliaries such as air conditioning are used or when cars are driven in cold weather.

Divergence between official and real-world CO_2 emissions values for selected countries, 2001-2014



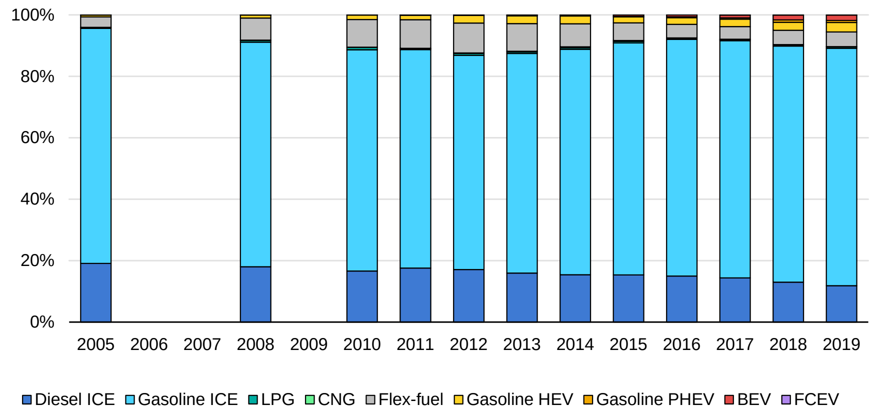
Note: NEDC = New European Driving Cycle; CAFE = corporate average fuel economy; EPA = Environmental Protection Agency.
Source: GFEI (2019), Fuel economy in major car markets: Technology and policy drivers 2005-2017

In 2018, a 14% gap persisted between rated fuel consumption on the Worldwide Harmonized Light-Duty Vehicle Test Cycle and real-world fuel consumption of gasoline and diesel internal combustion engine vehicles.

Powertrain technology

The powertrain of a vehicle – the engine plus the drivetrain – generates the mechanical energy and distributes it to the wheels. Powertrain technologies determine the conversion efficiency of vehicles and therefore play a major role in the rated specific fuel consumption and tailpipe CO_2 emissions.[1]

World average light-duty vehicle sales share by powertrain technology



Source: IEA analysis based on IHS Markit database.

As of 2019, gasoline and diesel internal combustion engines were the dominant powertrains globally, together accounting for almost 90% of sales. Certain markets, such as Europe, India and Korea, have high shares of diesel engines on their roads, while gasoline engines dominate in others, such as China, Canada and the United States. Similarly, sales of other alternative powertrains are not evenly distributed, but concentrated in certain markets.

Fuel consumption of powertrain technologies

Gasoline engines have the highest average rated fuel consumption at 7.5 Lge/100 km. The rated average fuel consumption of diesel engines is 17% lower due to their higher efficiency. Gasoline hybrid electric vehicles have gasoline internal combustion engines that can operate at maximal efficiency due to the hybrid system and can recover energy when braking, which results in an average fuel consumption 36% lower than conventional gasoline internal combustion engines. The average fuel consumption of diesel engines increased by 6% globally between 2017 and 2019 as sales of smaller, fuel-efficient vehicles with diesel engines have declined.

Electric vehicles (including battery and plug-in vehicles) have a much lower specific energy consumption because electric motors have an intrinsically higher conversion efficiency than internal

[1] The powertrain technologies assessed in this study are gasoline internal combustion engine (ICE), diesel ICE, flex-fuel ICE, compressed natural gas (CNG) ICE, liquefied petroleum gas (LPG) ICE, hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs).

combustion engines. Battery electric vehicles have an average rated energy consumption of 1.7 Lge/100 km and PHEVs 3.0 Lge/100 km.

Within each segment and powertrain, the efficiency of internal combustion engine powertrains has improved. For example, the rated fuel consumption of gasoline internal combustion engine vehicles in the medium car segment sold in 2019 was nearly 20% lower than in 2010. These fuel economy improvements are evident even as vehicle, weight, power and size have either remained constant or increased within each segment.

Between 2017 and 2019, the rated fuel consumption of gasoline engine powertrains decreased within most vehicle segments in China, in the United States, and in emerging market and developing countries. The reduction in fuel consumption in the United States was notably slower than it was between 2010 and 2017. In Europe, rated fuel consumption of gasoline engine vehicles increased within all segments except for large SUVs between 2017 and 2019. This suggests that in Europe manufacturers have made less effort to improve the efficiency of existing powertrains and that consumers have valued fuel efficiency less. This effect is even more pronounced for diesel vehicles, for which sales have declined markedly since the diesel emissions scandal.

Representative conversion efficiencies and sales shares for powertrains in light-duty vehicles, 2019

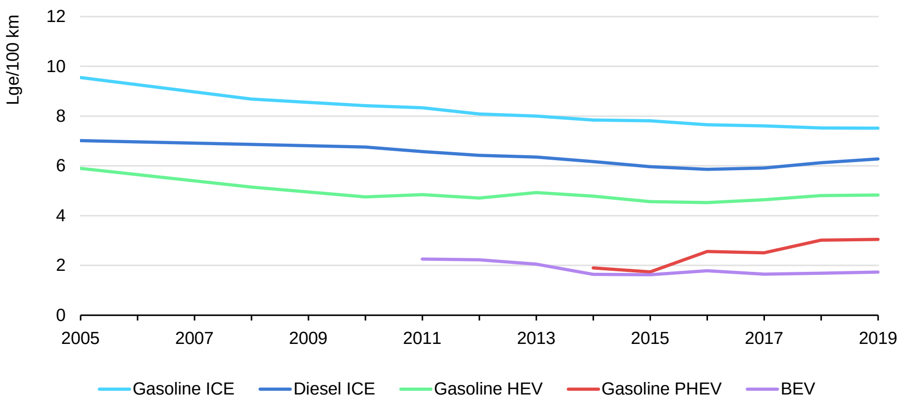
Powertrain	Efficiency	Sales share
Gasoline ICE	22%	74%
Flex-fuel ICE	22%	4%
Diesel ICE	29%	13%
CNG and LPG ICE	20%	<1%
Hybrid electric	36%	3%
Plug-in hybrid	46%	<1%
Battery electric	75%	2%
Fuel cell electric	55%	<0.1%

Notes: Representative conversion efficiency considers new vehicles sold in 2019 in the medium car segment, across OECD member countries.

Diesel

Historically, Europe has had a high sales share of diesel engines due to a fuel taxation scheme favouring their uptake. In 2019, the European Union was the largest market for diesel engines and had a diesel share of 37%. The country with the highest diesel share in 2019 was Turkey (59%). Other countries with high diesel shares include India (40%) and Korea (33%).

World average fuel consumption by powertrain, 2005-2019

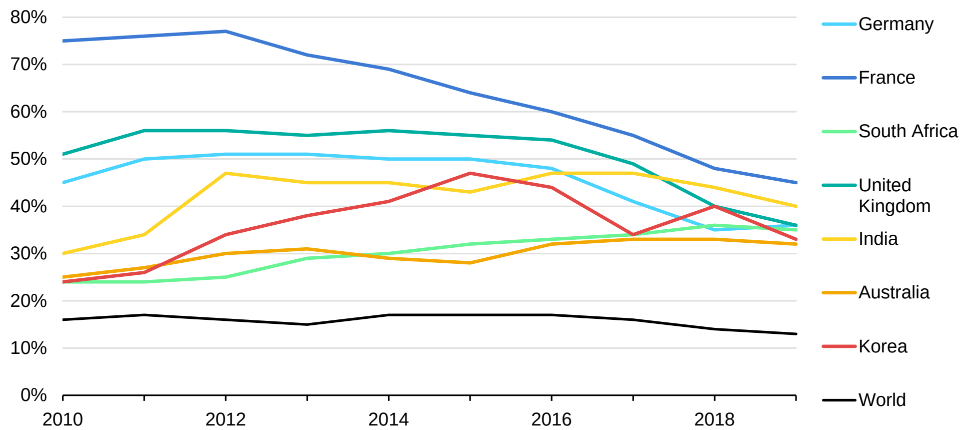


Source: IEA analysis based on IHS Markit database.

A major trend in the global car market is the drop in the sales share of diesel vehicles after 2015. Globally, between 2015 and 2019 diesel vehicle sales shares declined from 15% to 12%. Sales dropped from 51% to 37% in Europe, by 14% in Korea and by 3% in India.

These declines came in the wake of the 2015 diesel emissions scandal, which increased regulatory pressure and reduced consumer interest in diesel vehicles. Since 2014, the stringency of pollutant emissions standards in Europe has increased markedly, especially for diesel vehicles. The need to comply with these stricter pollutant emissions standards eroded the cost advantages of diesel cars, especially for small and medium vehicles, segments where the decline in diesel sales shares has been fastest.

Diesel vehicle sales share



Source: IEA analysis based on IHS Markit database.

The reduction in diesel vehicle sales was mostly offset by a rise in sales in gasoline light-duty vehicles by 3% between 2015 and 2019, and of hybrid electric vehicles by 1%. Given the differences in fuel economy between gasoline, diesel and HEV powertrains, this trend has slowed the reduction of rated fuel economy.

Flex-fuel vehicles

Flex-fuel vehicles have engines that burn ethanol-rich gasoline blends. These vehicles generally have higher fuel consumption than their gasoline equivalents. Flex-fuel vehicles accounted for 5% of global light-duty vehicle sales in 2019. Most of the uptake in this powertrain has occurred in Brazil, where this technology holds a sales share of almost 90%. Canada and the United States are the only other markets where this powertrain has non-negligible sales shares, of around 5% in 2019.

CNG and LPG

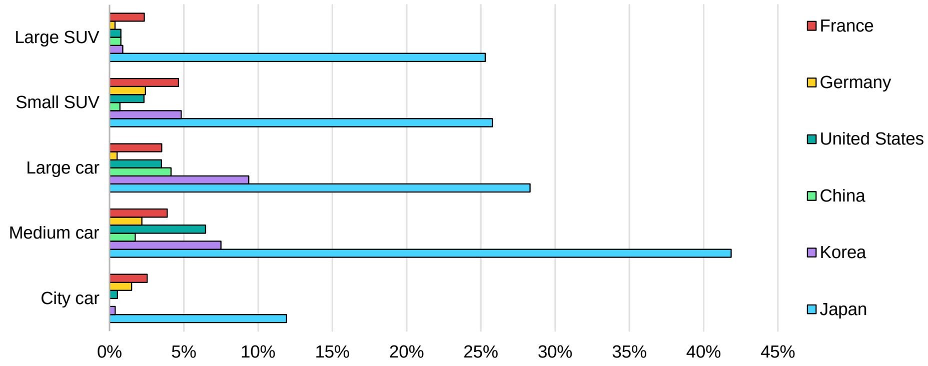
At a global level, internal combustion engine vehicles running on CNG or LPG played a more limited role, with a combined sales share below 1%. Their normalised fuel consumption tends to be higher than gasoline engines. Of the countries assessed in this study, only Italy, Korea and Ukraine had a combined sales share above 5% in 2019. Moreover, only Italy had a sales share for CNG vehicles above 2%.

Hybrid electric vehicles

Gasoline hybrid electric vehicles represented 3% of global light-duty vehicle sales in 2019. Japan registered exceptionally high penetration rates of hybrid electric vehicles in 2019 at close to 20%, followed by Korea at 6%. However, few other countries in 2019 had a sales share above 2% for hybrid electric vehicles.

Hybrid electric vehicles are mostly sold in the medium and large car segments, as these vehicles tend to appeal to consumers looking for fuel-efficient vehicles. This is true both for hybrid electric vehicle markets with high penetration such as Japan and Korea, as well as for the United States. Fewer SUVs tend to be hybrid electric vehicles.

HEV sales shares by segment in selected countries, 2019



Source: IEA analysis based on IHS Markit database.

Thanks to their lower fuel consumption and high market share, hybrid electric vehicles significantly reduce average fuel consumption. Without hybrid electric vehicles, the average fuel consumption would have been 2.8% higher in Japan and 1.4% higher in Korea. In markets with lower penetration, such as the United States and Europe, the impact is just under 1%.

Zero-emission vehicles

Electric vehicles had a combined global sales share of 2.4% in 2019. Electric vehicle uptake slowed in 2019 from previous years. Despite not being covered in the latest Global Fuel Economy Initiative dataset, global electric vehicle sales in 2020 increased by 41% year-on-year.

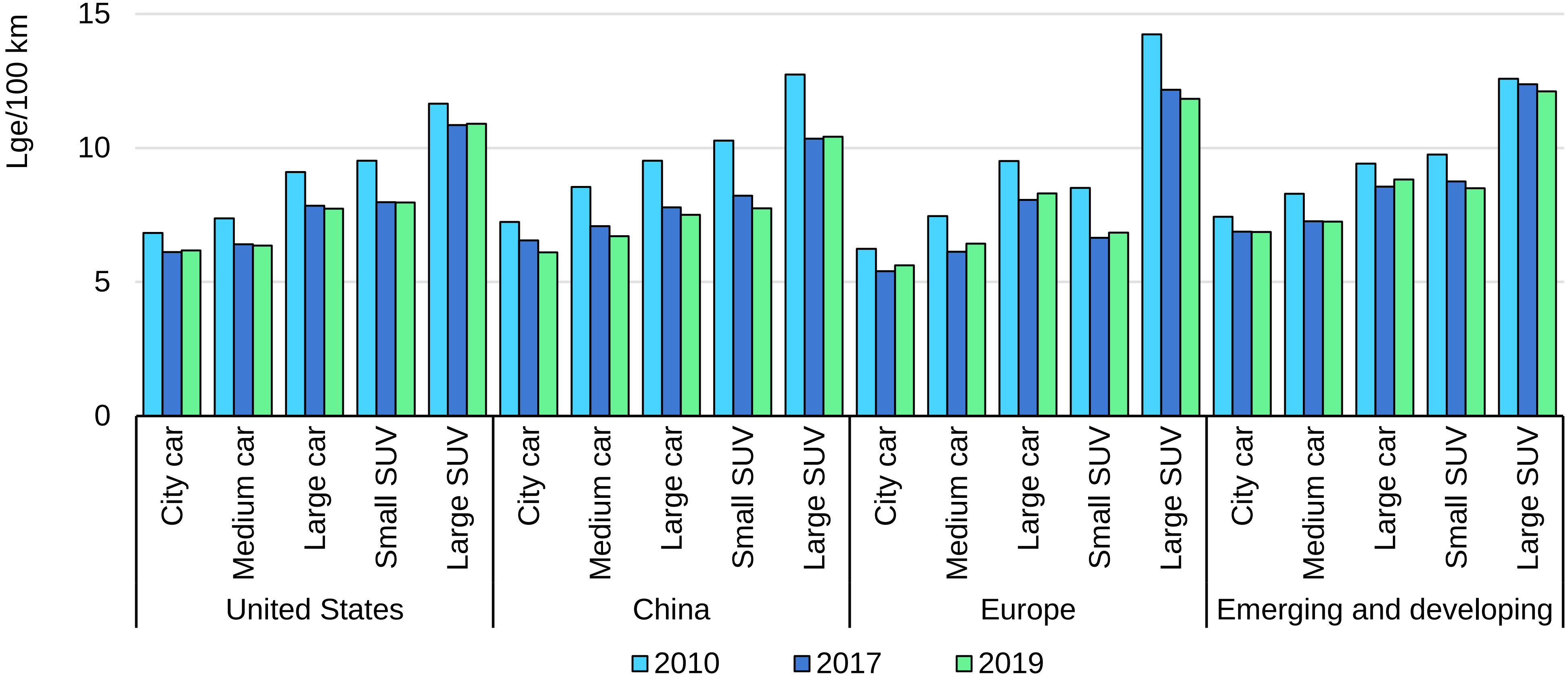
The markets covered in this analysis with the highest electric vehicle sales shares were China (4.3%), Germany (3.1%), the United Kingdom (2.9%), Canada (2.9%) and France (2.6%). While the rated fuel consumption of plug-in hybrid electric vehicles increased as more models have been sold in the SUV segments, the fuel consumption of battery electric vehicles[2] remained stable between 2015 and 2019.

The adoption rate of fuel cell electric vehicles in 2019 was very limited, as only three models are available globally. Korea had the highest sales share, at just above 0.1%.

[2] To compare the fuel consumption of BEVs with ICEs, the energy consumption of BEVs can be converted to litres of gasoline equivalent. The conversion is based on a constant factor representing the energy content of 1 litre of gasoline (33.5 megajoules per litre, or 9.3 kWh/L).

The pace of reductions in average fuel consumption of gasoline internal combustion engine vehicles has slowed down

Average fuel consumption of gasoline internal combustion engine vehicles within each segment, 2010, 2017 and 2019

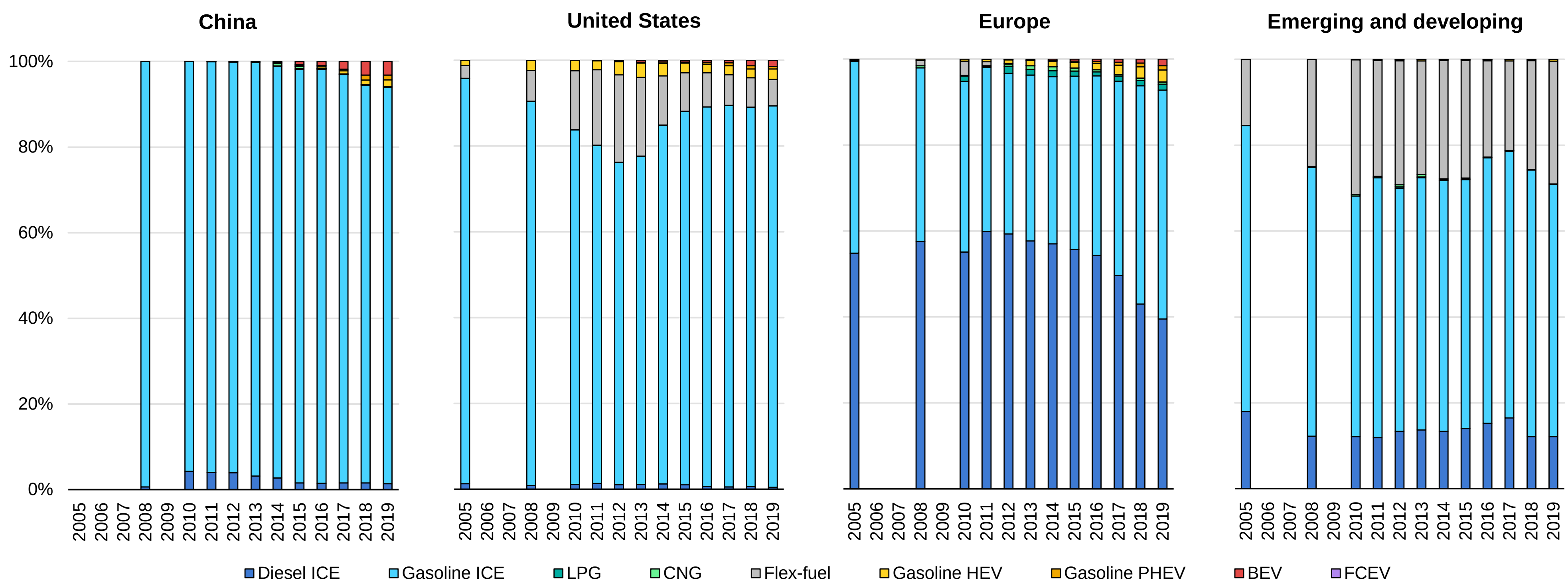


Notes: Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, the Russian Federation (hereafter, "Russia") and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Diesel sales are falling in Europe, while the uptake of electrified vehicles is low but increasing in major markets

Evolution of light-duty vehicle sales share by powertrain in key regions



Notes: Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Size segment

Light-duty vehicles can be classified into size segments: city car, medium car, small SUV,[1] large car, large SUV and van/light commercial vehicle. There is no official definition of vehicle size segments, but the consistent classification of light-duty vehicles across regions and years adopted in this study is a means to assess trends in vehicle markets. The table below shows the segmentation of some high-selling vehicle models. Associating vehicle size segments with their underlying attributes (power, weight, footprint and displacement) provides a way to explore how consumer choices affect rated fuel economy and tailpipe CO_2 emissions.

Vehicle models representative of each market segment

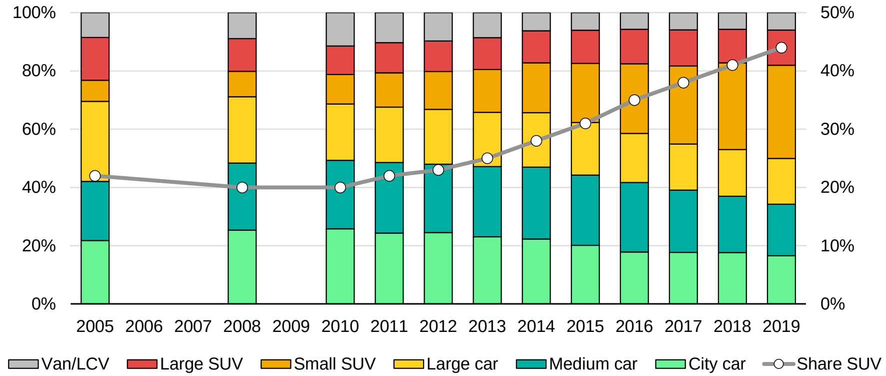
Segment	Vehicle models
City car	Honda Fit, Chevrolet Onix, Renault Clio, Fiat 500
Medium car	Volkswagen Lavida, Volkswagen Golf, Honda Civic,
Large car	Audi A4, Toyota Camry, Honda Accord,
Small SUV	Toyota RAV 4, GWM Haval H6, Hyundai Creta,
Large SUV	Ford F-150, Toyota Hilux, Volco XC90
Van/LCV	Mercedes Vito, Renault Kangoo, Wuling Rongguang

Source: IEA analysis based on IHS Markit database.

Trends in vehicle segment market shares

Small SUVs were the most sold size segment in 2019. The expansion of this size segment has been a key trend over the last decade, to varying degrees across all regions. The combined sales share of small and large SUVs grew from 20% in 2010 to almost 45% in 2019, with small SUVs contributing over 90% to the overall trend. From 2017 to 2019, however, this trend slowed – the compound annual growth rate declined to 7.5% from 10% between 2010 and 2017 – largely due to a slowdown in SUV adoption in China.

Global light-duty vehicle sales shares by segment, 2005-2019

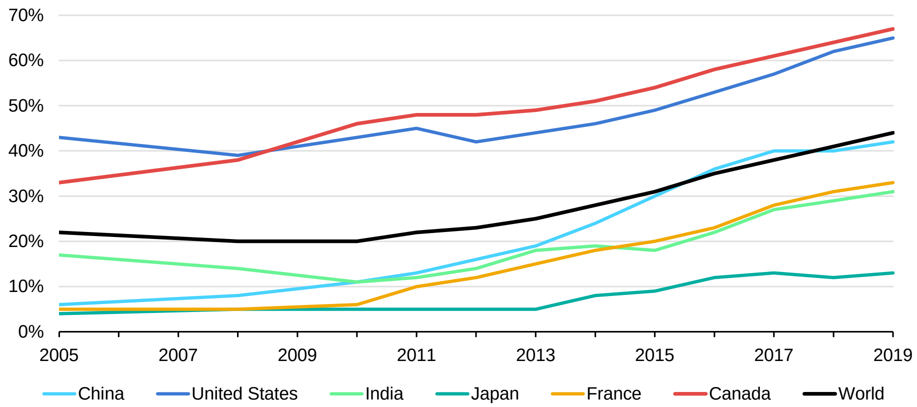


Source: IEA analysis based on IHS Markit database.

[1] Small and large SUVs include pickup trucks.

The uptake of small SUVs has been accompanied by declining shares of city cars and medium cars, with limited changes in sales shares of large SUVs and vans/light commercial vehicles. In particular, city cars, which in 2010 accounted for the lion's share of light-duty vehicle sales, accounted for less than one-fifth of all new light-duty vehicle sales in 2019. This is largely due to growing consumer preferences for larger vehicles. In addition, manufacturers have an incentive to increase marketing these vehicles, as they yield higher profit margins. Given that small SUVs have been replacing more fuel-efficient cars, this trend has partially offset the impact on fuel economy of technical improvements and the uptake of electric vehicles.

SUV sales shares in selected countries



Note: SUVs include both small SUVs and large SUVs.
Source: IEA analysis based on IHS Markit database.

Differences in the sales shares of different segments across countries reflect a variety of socio-economic, cultural and geographical factors. Advanced economies with low population densities and low fuel prices tend to have a larger share of SUVs; the sales shares of SUVs in 2019 were highest in Canada (67%), Australia (66%) and the United States (65%). Low fuel taxation (and hence low fuel prices) give consumers in these countries less incentive to buy fuel-efficient vehicles, and long distances travelled add to the appeal of more spacious, more comfortable cars.

In contrast, Japan registered the lowest rate of SUV adoption in 2019 due to higher fuel prices, short travel distances, the high density of cities and policies encouraging the purchase of kei-cars – very small, lightweight vehicles that the government has promoted since 1949. In Europe, fuel prices and distances are intermediate between the levels in Japan and in the United States. This helps to explain the more muted growth in the region's SUV sales shares, which remained below 40% in 2019.

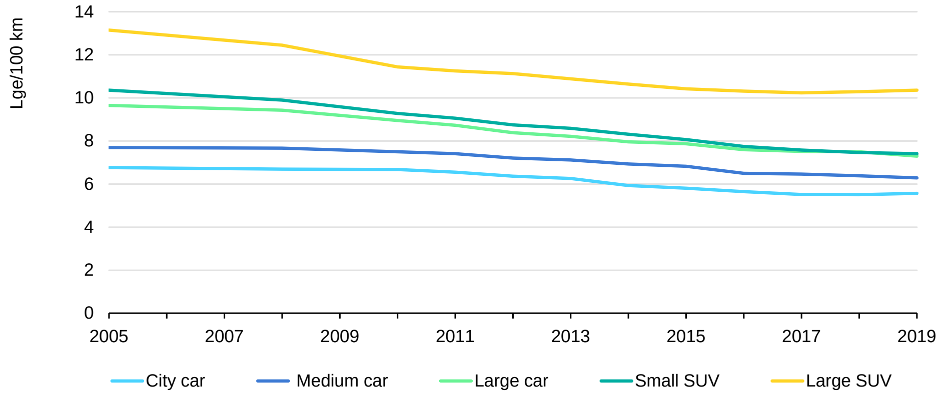
Over the last decade, China has experienced the highest expansion of the SUV segment, with sales shares growing from around 10% in 2010 to 42% in 2019. This reflects a growing preference among the burgeoning Chinese middle class for these vehicles. In emerging market and developing countries, SUV sales shares have traditionally been high because of the benefit these vehicles offer in regions with poor road conditions. India is a notable exception, perhaps because high fuel prices have curbed the demand for SUVs.

Fuel consumption by vehicle segment

As vehicle weight, footprint and power increase, so does fuel consumption. City cars have the lowest average fuel consumption (5.6 Lge/100 km), followed by medium (6.3 Lge/100 km) and large cars (7.3 Lge/100 km). Large SUVs have a global average fuel consumption of 10.4 Lge/100 km, 42% higher than large cars. Small SUVs have an average fuel consumption of 7.4 Lge/100 km, roughly equivalent to that of large cars.

Since 2010, the vehicle segment in which fuel economy has improved the most (20%) is small SUVs. As small SUVs have transitioned from a niche segment to the most sold segment, average vehicle weight fell by 6% and power by 4%. Large SUVs have improved less than half as much as their smaller counterparts (9%), as their average power increased by 12%, and their weight decreased 2%.

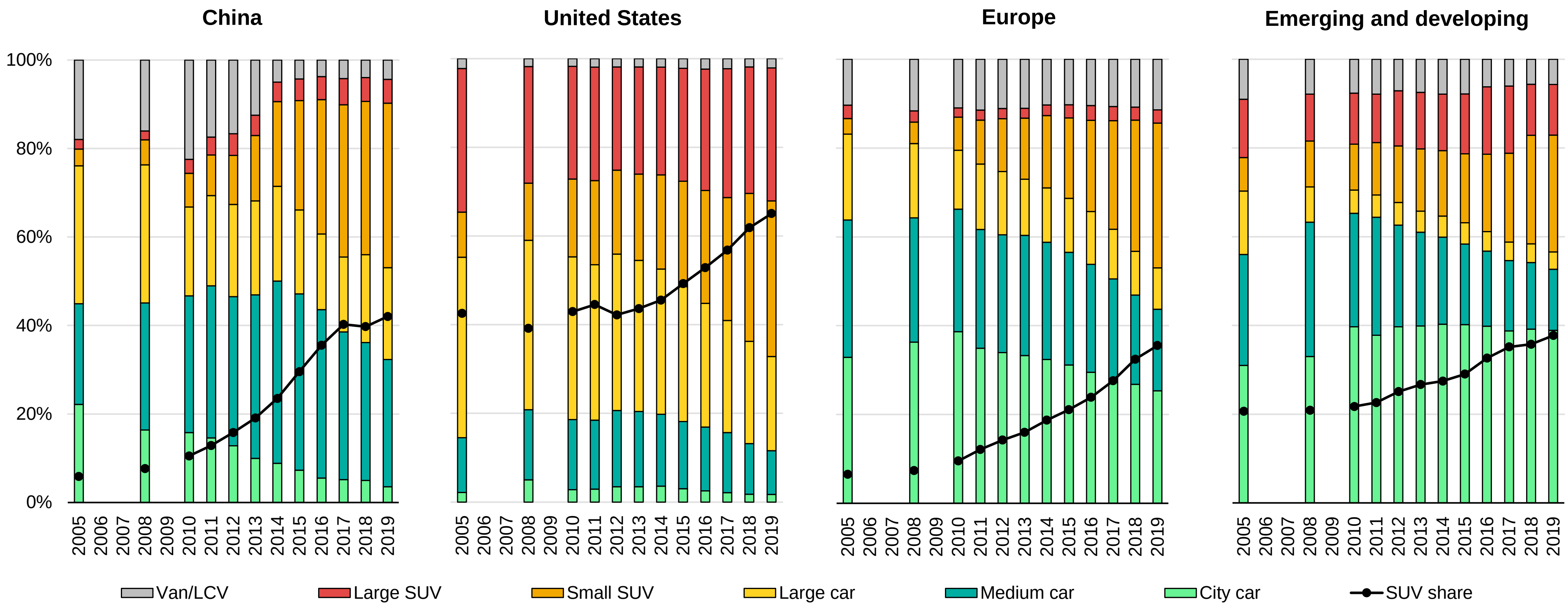
Fuel consumption across vehicle size segments



Source: IEA analysis based on IHS Markit database.

Sales of SUVs are rising in all key light-duty vehicle markets

Evolution of light-duty vehicle sales share by size segment in key regions



Notes: Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.
Source: IEA analysis based on IHS Markit.

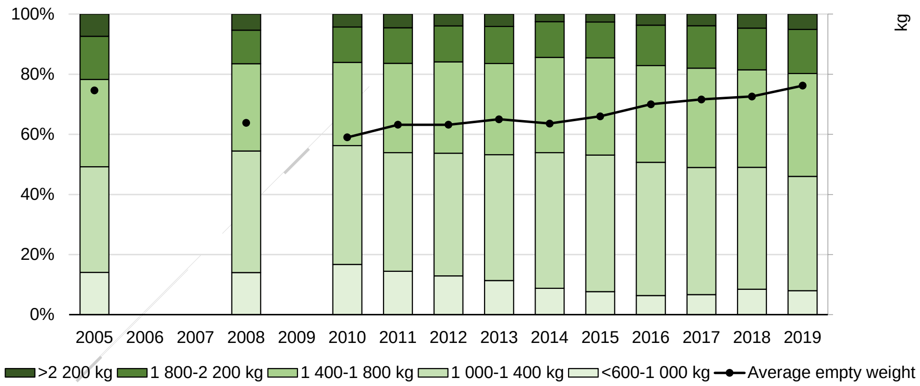
Vehicle weight

Vehicle weight is an important determinant of fuel consumption.[1] In internal combustion engine powertrains, 100 kg of additional kerb weight results in an additional 0.3 Lge/100 km and 9 g CO_2/100 km.[2] This is due to the fact that vehicle mass is proportional to inertial forces, which need to be overcome during acceleration, thus increasing fuel consumption.

From 2015 to 2019, the global average sales share of light-duty vehicles with a kerb weight of less than 1 400 kg (normalised with unspecified vehicles) fell by 7%. Over the same period, vehicle sales above 1 800 kg increased by around 5%. The share of vehicles between 1 400 kg and 1 800 kg also grew.

Vehicle weights by size segment vary little among different global areas,[3] so the distribution and variation of weight classes in a given market are largely explained by the distribution of size segments. Hence the overall increase in the average weight of vehicles sold globally arises from the decline in sales shares of city and medium cars (which mostly weigh below 1 400 kg) and the accompanying surge in sales of small SUVs. Weight increases within a size class can sometimes be attributed to increased vehicle safety regulations.

Global average light-duty vehicle sales shares by weight



Source: IEA analysis based on IHS Markit database.

Regional trends in vehicle weight

The trend of growing average vehicle weight is common to all light-duty vehicle markets, but it is more pronounced in certain markets. In the United States, average vehicle weight has remained steady over the last decade even though the percentage of vehicles weighing less than 1 400 kg declined from 18% in 2010 to 14% in 2019. Vehicle weight has remained stable mostly because the sales share of SUVs have grown at the expense of large cars, which

[1] Vehicle kerb weight measures the empty vehicle mass (including standard equipment and all operating fluids such as motor oil and coolant), excluding fuel and any passenger or cargo load.

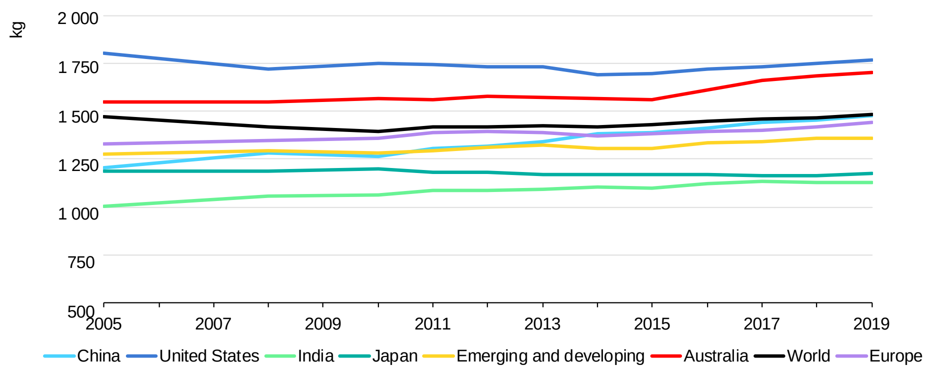
[2] The relationship varies by powertrain. More details were given in the previous edition of this report.

[3] Within each size segment, vehicle weight has mostly remained constant since 2010. A possible explanation is that increased weight due to higher safety and comfort features has been offset by lightweighting improvements.

weigh more than small SUVs. The sales share of large cars fell by 15% in the United States between 2010 and 2019.

China has experienced the fastest growth in vehicle weight over the last decade; the share of vehicles below 1 000 kg declined dramatically, from 23% in 2010 to 1% in 2019. In emerging market and developing countries, the share of vehicles below 1 000 kg decreased from 21% in 2010 to 7% in 2019.

Average vehicle weight across major light-duty vehicle markets

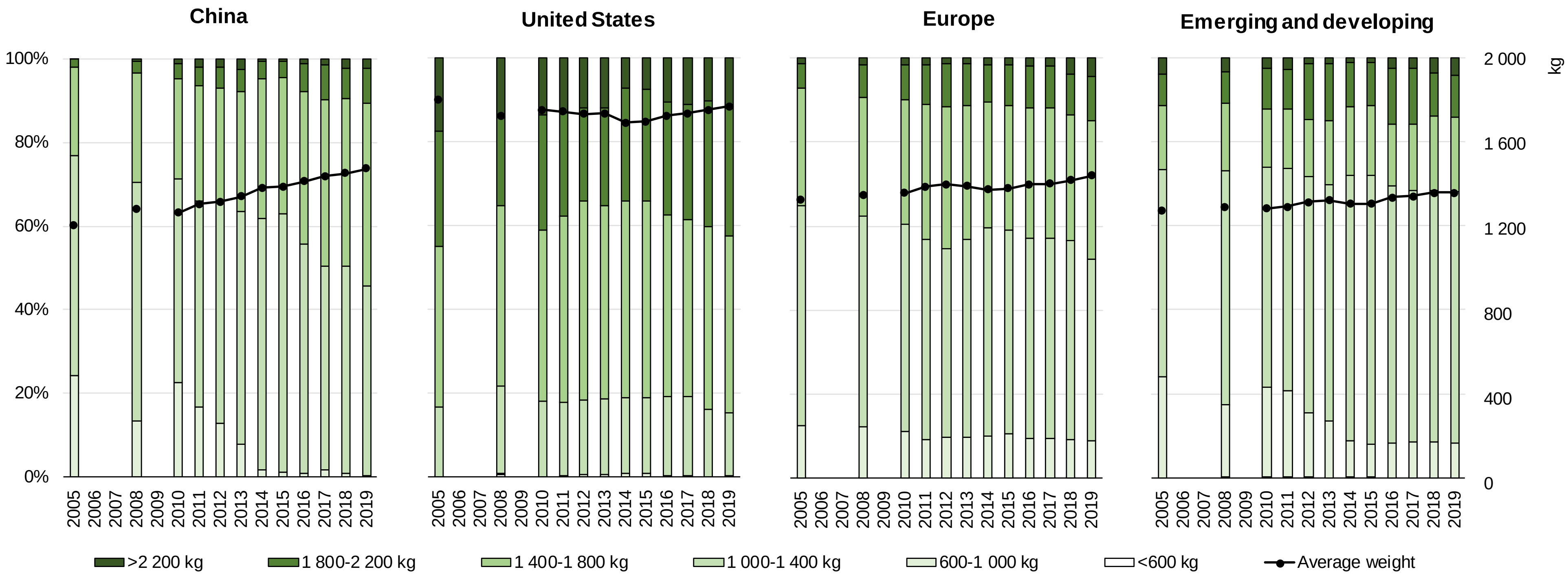


Source: IEA analysis based on IHS Markit database.

Some of the lowest average vehicle sales weights, of around 1 100 kg, are found in India and Japan. Both these countries have a high share of city cars and medium cars. While in India this trend is mostly due to the affordability of smaller vehicles, in Japan it can be explained by the kei-car phenomenon. The Japanese government applies a lower tax to these smaller vehicles, thus creating an incentive for consumers to choose them.

The average weight of light-duty vehicles has been increasing in recent years, particularly in China

Evolution of light-duty vehicle sales share by weight in key regions



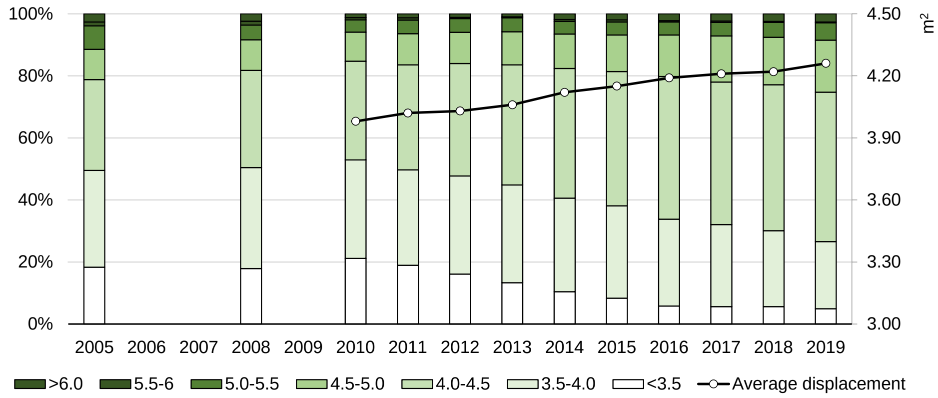
Notes: The secondary vertical axis shows the weighted-average kerb weight of the vehicle in kg. Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Vehicle footprint

Vehicle footprint is a commonly used proxy for vehicle size.[1] Footprint is used in some regulatory frameworks as a basis for adjusting corporate average fuel economy standards. The energy consumption of a vehicle is not directly connected to footprint (though it does depend on frontal area). However, footprint represents the overall size of a vehicle, which in turn is linked to fuel consumption.

World average light-duty vehicle sales share by footprint



Source: IEA analysis based on IHS Markit database.

Trends in vehicle footprint

The global average vehicle footprint of light-duty vehicle sales increased by 7% between 2010 and 2019, reaching almost 4.3 m^2. Light-duty vehicles sold in Canada had the largest average footprint (4.7 m^2) in 2019, with the United States at almost at the same level. Vehicles sold in India had the smallest average footprint (3.7 m^2). In 2019, only around one-quarter of light-duty vehicles sold globally had a footprint below 4 m^2, down from more than half in 2010. Meanwhile, the share of global light-duty vehicle sales with a footprint larger than 5 m^2 increased from 6% to 9%.

Average vehicle footprint has increased the most in China, rising 11% from 3.8 m^2 in 2010 to 4.2 m^2 in 2019. The share of vehicles within the footprint class 4.0 m^2 to 4.5 m^2 doubled from 30% in 2010 to 60% in 2019. This trend reflects a growing preference among Chinese consumers with rising incomes for more spacious vehicles.

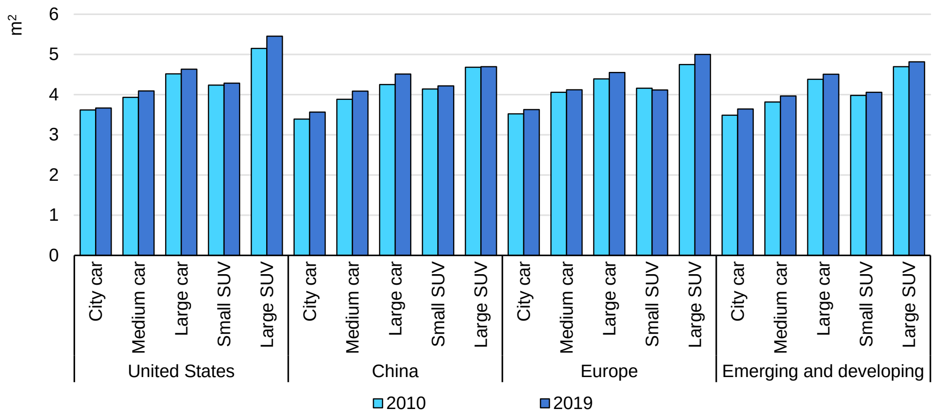
In Europe and emerging market and developing countries, the average vehicle footprint of new light-duty vehicle sales remained constant from 2010 to 2019. The main shift in these markets has been a transition from medium cars to small SUVs, which has not

[1] Vehicle footprint denotes the area defined by the vehicle wheelbase and axle width.

increased the average vehicle footprint since small SUVs have a similar footprint to medium cars (they are often built using the same platform).

In the United States, average vehicle footprint has been increasing since 2013. This trend can be explained by two factors. First, the market share of SUVs increased from 43% in 2010 to 65% in 2019. At the same time, while the average footprint of all segments increased, the footprint of large SUVs increased markedly, by 0.3 m^2, the largest increase of any vehicle segment in the world.

Vehicle footprint across size segments, 2019



Source: IEA analysis based on IHS Markit database.

Factors influencing vehicle footprint

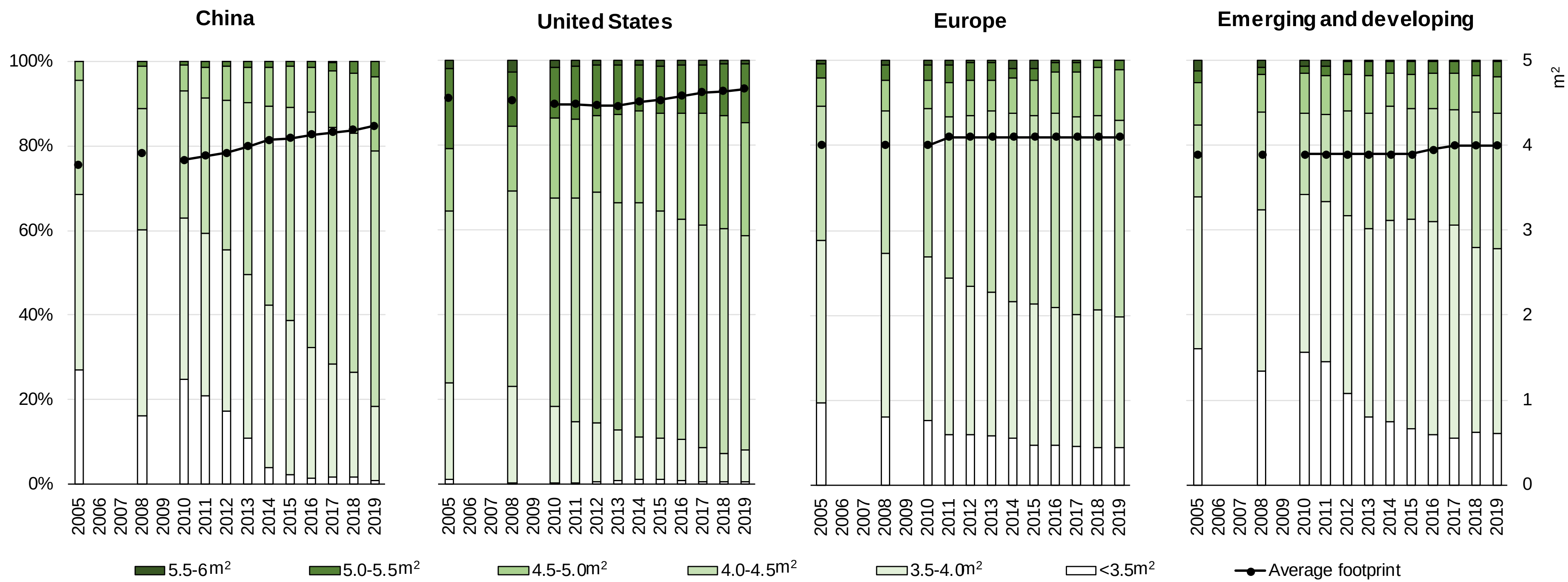
Vehicle footprint increased in nearly every size segment and region from 2010 to 2019 – by 1% to 6%, with the largest increase in the large SUV segment[2] – but it is not markedly different across the four major light-duty vehicle markets analysed. Large SUVs in the United States are an exception, being on average 16% larger than their counterparts in China and 10% larger than in Europe.

Overall, the average footprint within each country is determined by the distribution of size segments within the given market. As with vehicle weight, the rise in vehicle footprint over the last decade is explained by the growing market share of SUVs.

[2] In Europe the average footprint of the small SUV segment decreased by 1% from 2010 to 2019.

The average vehicle footprint of light-duty vehicles has been increasing in recent years

Evolution of light-duty vehicle sales share by weight in key regions



Notes: The secondary vertical axis shows the average vehicle footprint in m^2. Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Vehicle power

Vehicle power is related to the force that the powertrain can deliver to the vehicle.[1] For vehicles of the same weight and size, higher power delivers higher acceleration; holding acceleration constant, larger and heavier vehicles require more power.

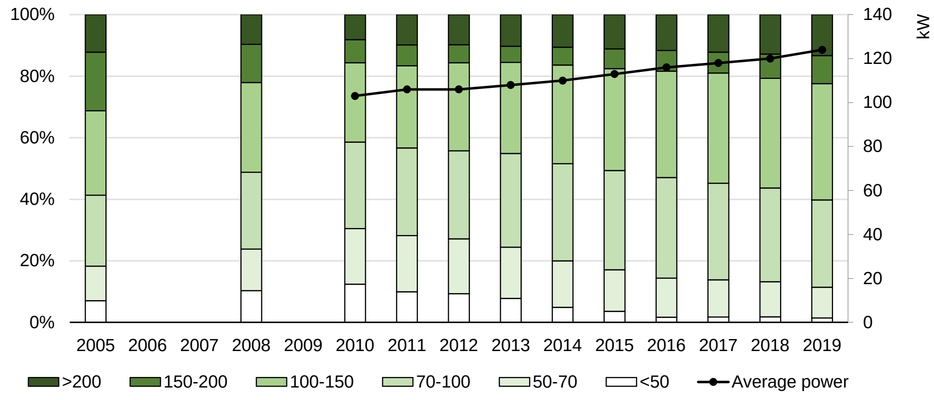
Higher vehicle power tends to increase fuel consumption for two reasons. Larger, heavier vehicles require more energy to move, and need higher engine power to provide satisfactory acceleration. In addition, higher-powered engines generally operate at much less than optimum efficiency in everyday driving conditions, so higher-powered cars tend to have lower engine efficiency than lower-powered equivalents.

Trends in vehicle power across regions

The global average power rating of light-duty vehicles sold in 2019 reached 124 kW, a 20% increase since 2010. The largest share of light-duty vehicles sold globally was those with a power rating between 100 kW and 150 kW (34%). In 2010, 10% of vehicles sold had power ratings below 50 kW, but very few of these vehicles were sold in 2019.

In 2019, light-duty vehicle sales in Canada had the highest power rating (184 kW), closely followed by the United States (182 kW). In the United States, average power has increased by 9.6% since 2010, mostly because of increases in the sales share and power of large SUVs, but also because power increased across all segments.

Evolution of world average light-duty vehicle sales share by vehicle power category



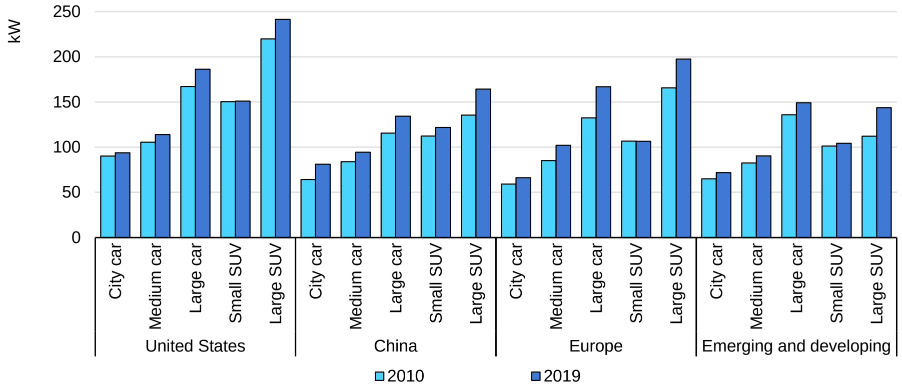
Source: IEA analysis based on IHS Markit database.

[1] Vehicle power refers to the rated power of the vehicle engine. In the case of hybrid electric vehicles and plug-in hybrids, this includes the power of the engine and the electric motor.

In China, the average power rating of light-duty vehicles was 115 kW in 2019, which is a staggering 37% increase since 2010. Chinese consumers have been purchasing larger vehicles that require more power, as well as smaller vehicles with higher acceleration.

In Europe, average vehicle power increased by 21% between 2010 and 2019, to reach 102 kW. This growth is on par with the increase observed in the United States, and increased uptake of larger vehicles is once again the major factor behind this trend. The lowest average vehicle power ratings are observed in emerging market and developing countries (94 kW), with light-duty vehicle sales in India having the lowest average power rating of 64 kW, 2.9 times lower than the average power rating in Canada.

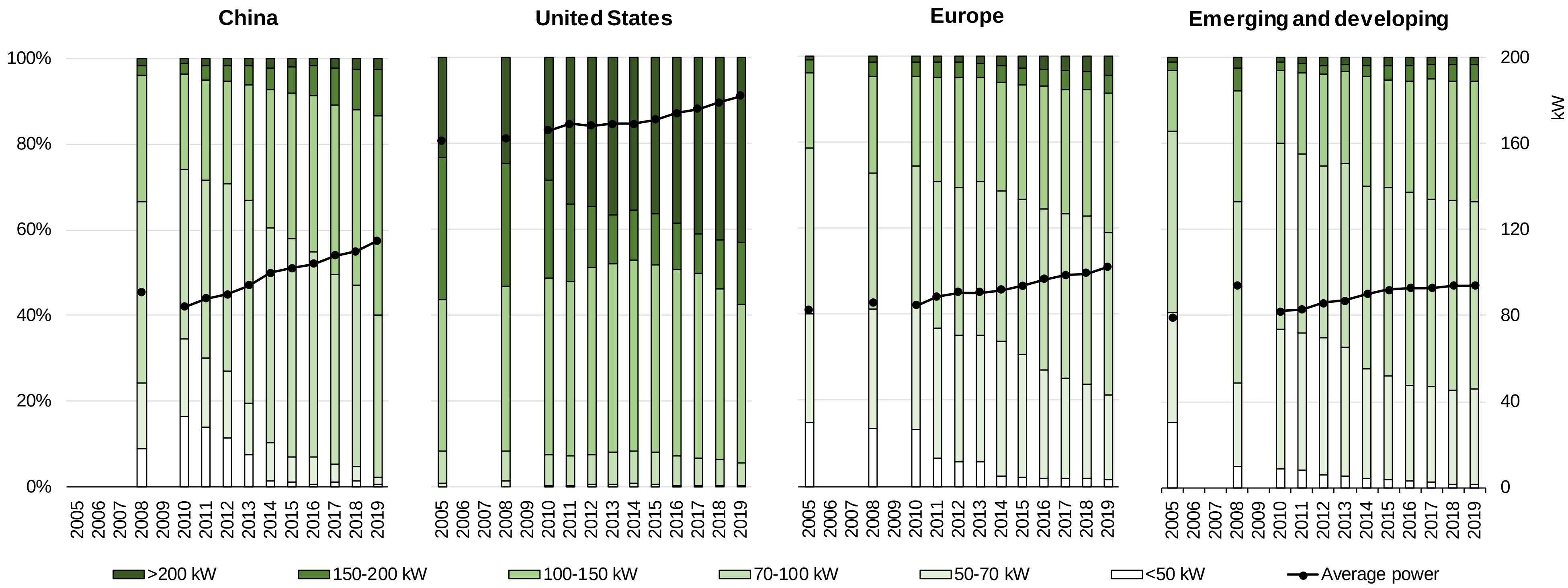
Power across size segments and regions, 2010-2019



Source: IEA analysis based on IHS Markit database.

The average power rating of light-duty vehicles has been increasing in recent years

Evolution of light-duty vehicle sales share by power rating in key regions



Notes: The secondary vertical axis shows the rated power of the vehicle in kW. Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Power-to-weight ratio

Not only have vehicles become larger over time in major vehicle markets, vehicle performance has also improved: vehicles have higher acceleration, top speed and towing capacity. One simple metric that can be used to represent vehicle performance is the ratio between rated power and vehicle weight.

Trends in power-to-weight ratio

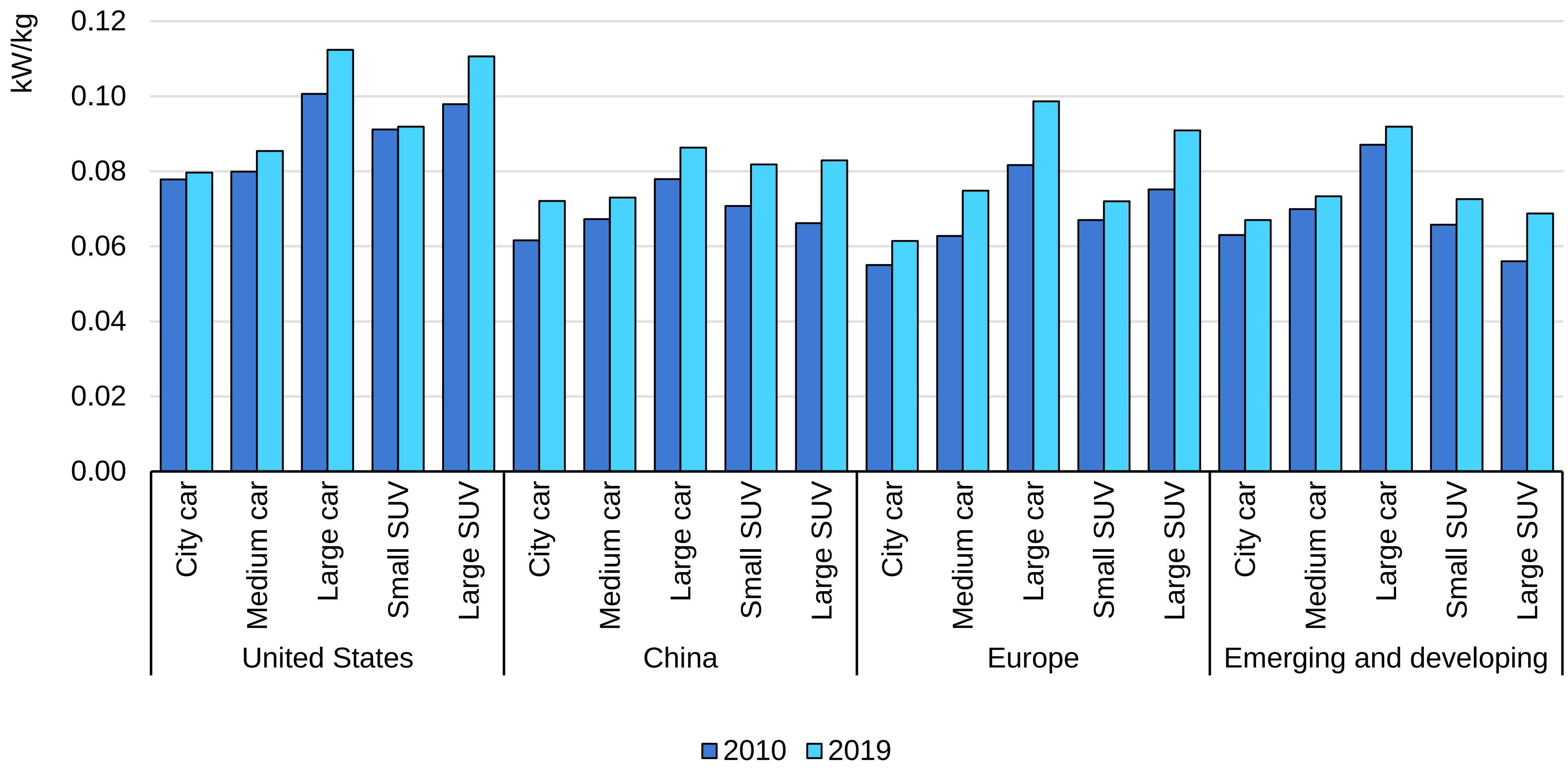
At a global level, all vehicle segments have undergone an increase in power-to-weight ratio. City cars underwent the largest increase between 2010 and 2019, of 16%, driven by the increase in China. Medium and large cars increased around 10%, while small SUVs remained mostly constant. Large SUVs experienced the second-largest increase, of 14%. Large SUVs are not only gaining an increasing share of the market, they are larger and have higher performance.

However, the performance of large SUVs varies widely across different markets. In China, Europe, and emerging market and developing countries, large SUVs perform less well than large cars but better than other segments (in China, large and small SUVs have comparable performance). In emerging market and developing countries, large SUVs have the lowest performance, possibly because in these markets they are valued more for their all-terrain capabilities than as luxury items.

In the United States, consumers have strongly moved towards larger and higher-performance vehicles, while fuel consumption has not improved significantly. Large SUVs have comparable performance to large cars, which tend to be the premium, highest-performing segment. The average large SUV in the United States in 2019 had a 10% higher performance than large cars in 2010.

All vehicle segments have higher performance, but the fastest increase was in city cars and large SUVs.

Power to weight ratio evolution by segment across regions, 2010-2019



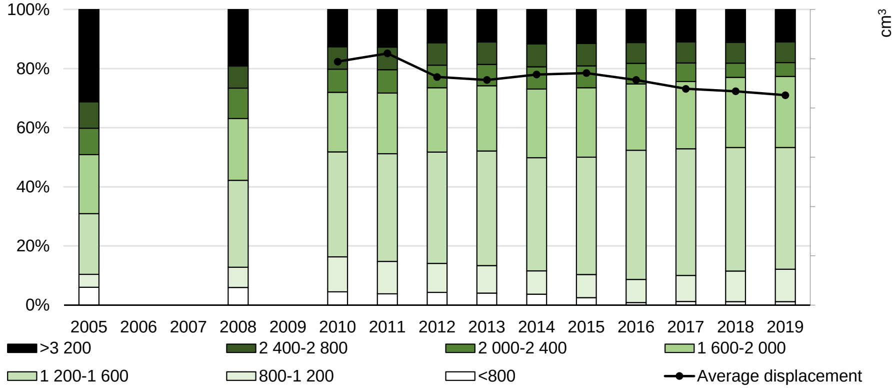
Note: Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.

Source: IEA analysis based on IHS Markit.

Engine displacement

Engine displacement – the combined volume of pistons within the cylinders of an engine – is not directly linked to fuel consumption. Rather, engine displacement depends on engine power and engine technology. Within a given engine technology, higher power requires higher engine displacement. However, technologies such as supercharging and turbocharging can enable higher power output for the same engine displacement, making engine “downsizing” possible. At a global level, the engine displacement of new light-duty vehicles has continuously decreased even as power has increased.

Global average light-duty vehicle sales share by engine displacement



Source: IEA analysis based on IHS Markit database.

Trends in engine size across regions

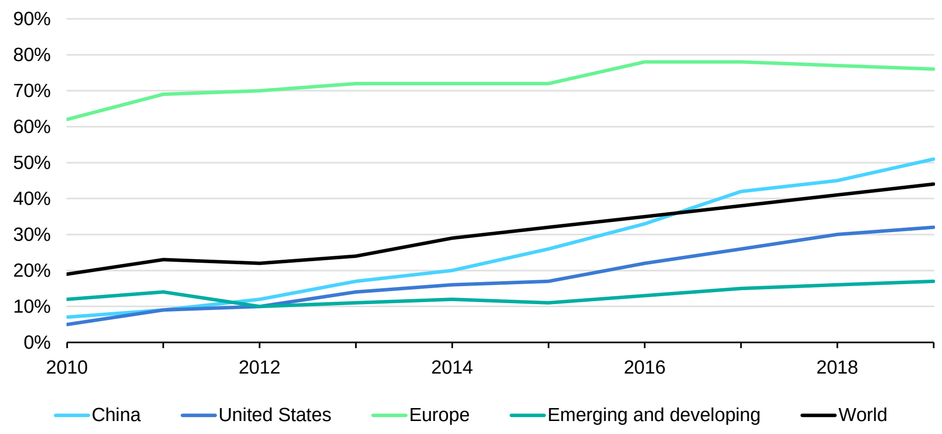
Light-duty vehicles sold in the United States had the highest average engine displacement in 2019 (2 800 cm^3), but this value has steadily decreased since 2010. High engine displacements are associated with high-powered vehicles, and a historical preference in the United States for naturally aspirated engines, which require more displacement per unit power than do turbocharged engines.

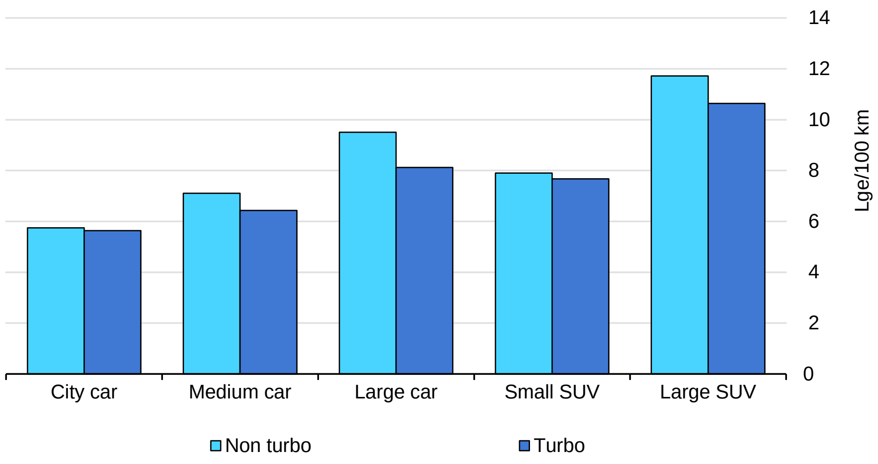
In China, average engine displacement of light-duty vehicle sales was 1 670 cm^3 in 2019. This value has fluctuated only slightly since 2010, while average power increased by 37%, reflecting the impact of technologies enabling smaller engines.

In Europe, average engine displacement across light-duty vehicle sales in 2019 was 1 571 cm^3, down 6% since 2010, while power has increased 21%. Emerging market and developing countries have a similar average engine size to Europe and this value has changed little since 2010. However, average power is 10% lower in emerging market and developing countries than in Europe, reflecting a higher share of naturally aspirated engines.

The global share of vehicles with turbochargers is increasing

Share of gasoline internal combustion engine new light-duty vehicles with mechanically aspirated engines in selected regions (left), average new fuel consumption for gasoline internal combustion engine light-duty vehicles by segment (right)

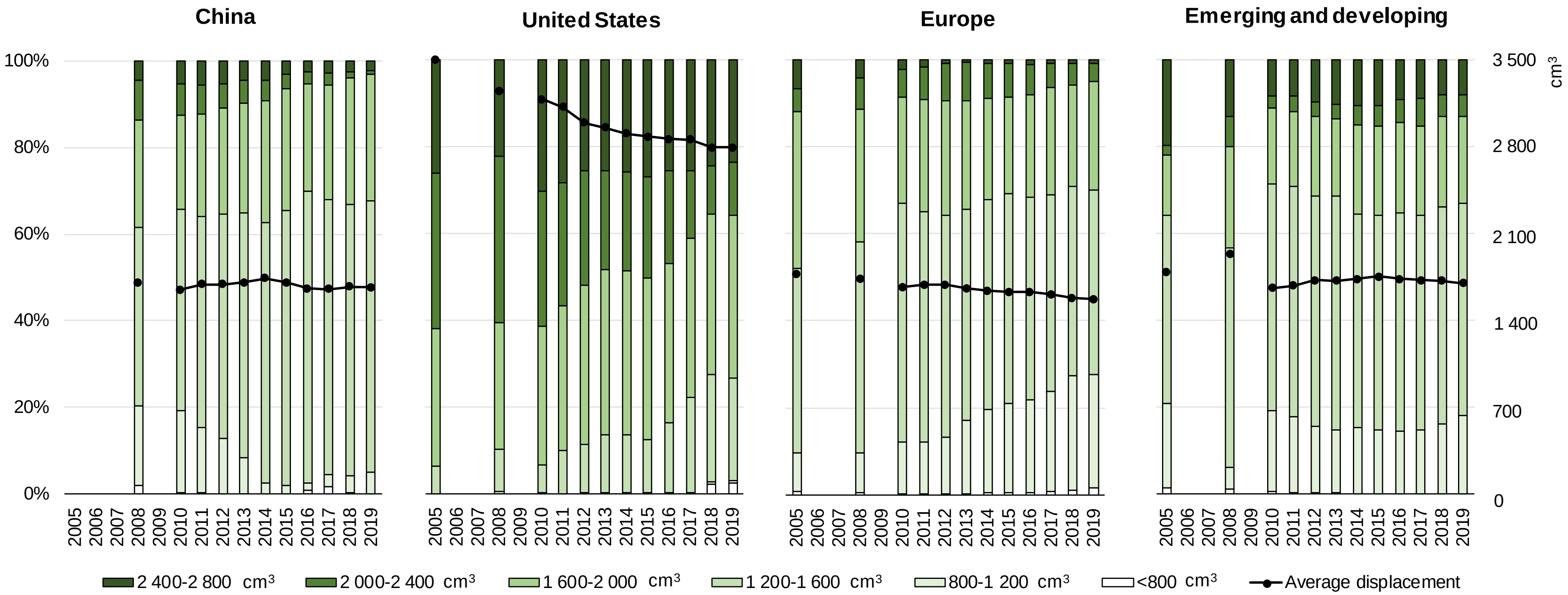




Notes: Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.
Source: IEA analysis based on IHS Markit database.

Engine size has decreased in Europe and the United States, and stayed constant in China and emerging market and developing countries

Engine displacement across regions, 2005-2019



Notes: The secondary vertical axis shows the displacement of the vehicle in cm^3. Emerging market and developing countries include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, Russia and Ukraine. Europe includes only France, Germany, Italy and the United Kingdom.
Source: IEA analysis based on IHS Markit database.

Regional variability in the vehicle attributes that determine fuel economy

Average vehicle parameters in each of the countries analysed, 2019

Year: 2019	Japan	France	Turkey	India	Italy	Germany	United Kingdom	Korea	Malaysia	China	Ukraine	South Africa
Fuel economy (Lge/100km)	5.5	5.5	5.5	5.7	5.7	6.2	6.3	6.4	7.1	7.2	7.3	7.4
Power (kW)		89	88	64	84	116	110	132	88	115	115	96
Empty weight (kg)	1 176	1 359	1 398	1 129	1 333	1 503	1 518	1 479	1 195	1 476	1 548	1 519
Footprint (m²)	4.1	4.0	4.1	3.7	3.9	4.2	4.1	4.5	3.8	4.2	4.2	4.1
Share of SUV	13%	33%	23%	31%	40%	33%	39%	39%	28%	42%	60%	49%
Share of hybrids	18%	3%	2%	0%	4%	2%	4%	6%	0%	2%	1%	0%
Share of electric vehicles	1%	3%	0%	0%	1%	3%	3%	3%	0%	4%	1%	0%
Share of diesel	3%	45%	59%	40%	45%	36%	36%	33%	0%	1%	34%	35%
Displacment (cm³)	1 604	1 451	1 520	1 367	1 463	1 675	1 630	2 033	1 494	1 671	1 892	1 804

Year: 2019	Brazil	Mexico	Argentina	Egypt	Chile	Indonesia	Philippines	Russia	Australia	United States	Canada	World
Fuel economy (Lge/100km)	7.5	7.6	7.8	7.8	7.9	8.1	8.2	8.3	8.3	8.6	8.6	7.1
Power (kW)	87	106	92	89	98	79	136	103	136	182	184	124
Empty weight (kg)	1 261	1 379	1 358	1 480	1 447	1 276	1 835	1 463	1 703	1 768	1 757	1 485
Footprint (m²)	3.9	4.0	4.1	4.3	4.1	3.9	4.2	4.1	4.3	4.7	4.7	4.3
Share of SUV	35%	38%	37%	39%	54%	23%	42%	44%	66%	65%	67%	44%
Share of hybrids	0%	1%	0%	0%	0%	0%	0%	0%	3%	2%	2%	3%
Share of electric vehicles	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	3%	3%
Share of diesel	9%	0%	19%	18%	27%	13%	0%	11%	32%	0%	1%	13%
Displacment (cm³)	1 484	1 908	1 725	1 760	1 821	1 552	2 527	1 923	2 294	2 790	2 826	1 926

Note: Fuel economy in [Worldwide Harmonized Light-Duty Vehicle Test Cycle](). In the latest dataset, statistics on vehicle rated power in Japan were not available.
Source: IEA analysis based on IHS Markit database.

Policies to promote low-emissions powertrains and slow down vehicle size increase

Policies to encourage the uptake of low-emission powertrains

To rapidly decarbonise the transport sector and decrease the fuel consumption of new cars, rapid and widespread uptake of low-emission vehicles is required. Two key policies that can accelerate the adoption of low-emission powertrains are feebates (also called "bonus-malus" in some countries) and corporate average fuel economy standards.

Bonus-malus scheme

The bonus-malus (or "feebate") policy scheme imposes a fee on the purchase of vehicles with rated specific CO_2 emissions (g CO_2/km) above a determined level, and a subsidy for the purchase of vehicles with CO_2 emissions below a specified level.[1] Although the policy directly targets CO_2 emissions performance, it indirectly affects vehicle weight and size, as larger, heavier vehicles tend to be less fuel-efficient. Notably, the policy can be revenue-neutral: revenue from fees on heavy, emissions-intensive vehicles can finance purchase subsidies for fuel-efficient, lightweight vehicles and electric vehicles. This characteristic sets it apart from pure incentive schemes, which can be very effective but are a drain on public budgets and thus are unsustainable in the long term. A feebate scheme was first introduced in France and has been effective in helping decrease CO_2 emissions. Other countries have adopted feebates, such as Sweden in 2018 and Italy in 2019.

Corporate average fuel economy standards

Among the most widespread regulatory instruments to encourage rapid adoption of efficient technologies are corporate average fuel economy (CAFE) standards. CAFE standards set mandatory fuel economy improvements across a specified time horizon that vehicle manufacturers must meet or face a penalty. The main benefit of this policy is that it gives freedom to manufacturers to choose how to best approach the regulatory requirements, and is therefore economically efficient.

Many CAFE regulations include extra incentives (often called "credits" or "supercredits") for zero-emission vehicles. While these can help to motivate manufacturers to sell zero-emission vehicles, they have in some instances effectively reduced the stringency of CAFE regulations. If such credits are awarded, it is important to ensure that they do not undermine the stringency of fuel economy standards.

CAFE standards have helped improve fuel economy, but between 2017 and 2019 they did not substantially push down fuel consumption in the United States and the European Union.[2] Most CAFE standards are not designed to encourage the sales of smaller vehicles, as targets are set proportionally to the weight or footprint of vehicles sold. However, by making fuel economy targets more difficult to achieve in heavier vehicles (for weight-based standards) or wider vehicles (for footprint-based ones), such standards can alter the profit-maximising production decisions of manufacturers and promote sales of lighter and smaller vehicles.

[1] France was one of the first countries to implement this type of policy. ACEA (2021) Tax Guide 2021.

[2] In Europe, an 11% drop in average CO_2 emissions occurred in 2020. See Chapter 1 for more details.

Policies to discourage vehicle weight and size increase

In certain markets, sustained sales growth in SUVs and large vehicles has muted or nearly completely offset progress in fuel economy over the last few years. However, policy makers can draw lessons from several notable examples of well-designed and effective regulatory schemes that address the observed increase in vehicle weights and sizes.

Japanese kei-cars

Japan, which has consistently had the lightest new light-duty vehicle sales among developed countries across all years in the database of the Global Fuel Economy Initiative, has perhaps the longest-running policy to encourage smaller cars. Since 1949, it has promoted very small, lightweight vehicles known as keijidōsha (kei-car). Kei-cars are subject to strict regulations limiting vehicle size, engine displacement and power.[1] The kei-car programme originated as a measure to advance motorisation in Japan after World War II and has been maintained to increase fuel efficiency and reduce CO_2 emissions. Several incentives encourage uptake of kei-cars, including reduced acquisition and insurance taxes, a 20% discount on rural highway tolls and exemptions from parking space registration requirements.[2] Over the past few decades, kei-cars have experienced significant market growth, reaching nearly one-third of new passenger car sales in Japan in 2018.

Weight-based taxes in Norway and France

Another example comes from Norway, which since 1955 has implemented a one-off registration (purchase) tax on internal combustion engine light-duty vehicles. The tax is based on vehicle kerb weight, and emissions of CO_2 and nitrogen oxides. The amount payable based on vehicle kerb weight is applied per kilogramme.[3] The components of the tax reinforce each other, resulting in purchase taxes that are significantly higher for large, heavy vehicles than for smaller, lightweight cars.

More recently, France has imposed a tax on heavy vehicles to curb purchases of SUVs and large cars. A weight limit of 1 400 kg was initially proposed, but because of concerns that it would hurt the French car industry, the limit was eventually set at 1 800 kg. The tax adds EUR 10 (USD 11.70) for every kilogramme over the 1 800 kg limit to the retail price. Battery and plug-in hybrid electric vehicles remain exempt from the tax.

[1] Current requirements: engine displacement < 660 cm^3, vehicle length <3.4 m, width < 1.48 m, height < 2.0 m.
[2] See Table 2 of www.lipscy.org/Japan_Transport_EnergyPolicy.pdf.

[3] At a rate of USD 3.05/kg between 501 kg and 1 200 kg, and USD 27.65/kg above 1 500 kg, increasing linearly.

Chapter 3. Well-to-tank greenhouse gas emissions

Defining and measuring well-to-tank emissions

This chapter describes the technologies and processes needed to produce, process and deliver various transport fuels to a vehicle. It explains how greenhouse gases are emitted at each step along this "well-to-tank" fuel supply chain and how these emissions vary across regions, technologies, and time.

This chapter focuses on the major fuels and energy carriers that currently supply energy to light-duty vehicles – or could in the near future:

- Oil products (automotive gasoline and diesel).
- Natural gas (associated and dedicated production).
- Biofuels (ethanol, biodiesel and biomethane).
- Electricity.
- Hydrogen.
- Synthetic fuels (using both biogenic and atmospheric carbon sources).

Data sources, methodology and system boundaries

Estimates of greenhouse gas emissions incurred along fuel supply chains were integrated into the IEA Mobility Model based primarily on internal IEA databases and on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies tool (GREET) developed by the Argonne National Laboratory in the United States. Whenever available, energy production, conversion and transport efficiencies were taken from IEA Energy Technology Perspectives energy supply modelling. Historical data are calibrated to match the World Energy Balances, and projections are based on IEA modelling.

The major greenhouse gases associated with fuel supply chains – CO_2, methane and nitrous oxide – are covered in each pathway, and a broader set of greenhouse gases is considered in the processes that draw from the GREET model. Tank-to-wheel coverage in the Mobility Model is limited to CO_2 emissions from fossil and biogenic fuel combustion; inclusion of further greenhouse gases is a high priority. Further details on the data sources, assumptions, methods and potential improvements are provided in Annex 2.

In cases where processes are not explicitly modelled (e.g. farming operations and fertiliser and pesticide application), GREET default values are reported. Alternative co-product allocation methods, as well as estimates of direct and indirect land-use change, have been input into the Mobility Model, together with emissions estimates developed in the JEC Consortium's Well-to-Tank Report v5.

For each fuel and energy carrier, a flow chart shows the system boundaries considered and indicates the representative share (or range) of greenhouse gas emissions incurred in each process. Greenhouse gas emissions reported across all fuel supply chains do not include emissions incurred in building and maintaining infrastructure for energy production, conversion, transport or dispensing, such as thermal power plants, solar farms or wind turbines (production); electrolysers for hydrogen production, refineries or farming equipment (conversion); pipelines, trucks and ships (transport); or refuelling stations or electric vehicle supply equipment (dispensing). However, they generally include emissions incurred in operating these plants and processes (and others).

Global warming potentials

CO_2, methane, nitrogen oxides and other greenhouse gases have different climate impacts that depend on their capacity to trap heat and how long they persist in the atmosphere. Converting emissions of all greenhouse gases to their carbon dioxide equivalents (CO_2-eq) is a common way of comparing their climate impacts. The CO_2 equivalent of a given greenhouse gas species is based on its global warming potential – usually the amount of heat it traps, relative to the amount that CO_2 would trap over the same time span. For example, the 100-year global warming potential for methane is 28 since 1 kg of methane is expected to trap the same amount of heat as 28 kg of CO_2 over 100 years. As such, 1 kg of methane emissions can be expressed as 28 kg CO_2-eq.

While 100-year global warming potentials are often reported, 20-year and 50-year time horizons can be estimated. Estimates based on a shorter time horizons result in higher global warming potentials for greenhouse gases that have shorter atmospheric lifetimes. For example, methane's 100-year potential is 28 while its 20-year potential is 84. Therefore, the choice of time horizon has important implications for how global warming potentials inform greenhouse gas emissions reduction targets and strategies. Estimates of global warming potentials are routinely updated with each new report from the Intergovernmental Panel on Climate Change (IPCC), because they evolve as understanding of the underlying atmospheric chemistry and the interplay of changing atmospheric concentrations of greenhouse gases improves. This report adopts the latest 100-year global warming potential from the IPCC Fifth Assessment Report (AR5), as this is the metric on which well-to-tank data sources (e.g. greenhouse gas emissions intensity of electricity generation in IEA data and GREET) are generally benchmarked, and it is the metric on which countries' nationally determined contributions are benchmarked and communicated. The addition of reporting on 20-year global warming potentials is a potential area for future updates.

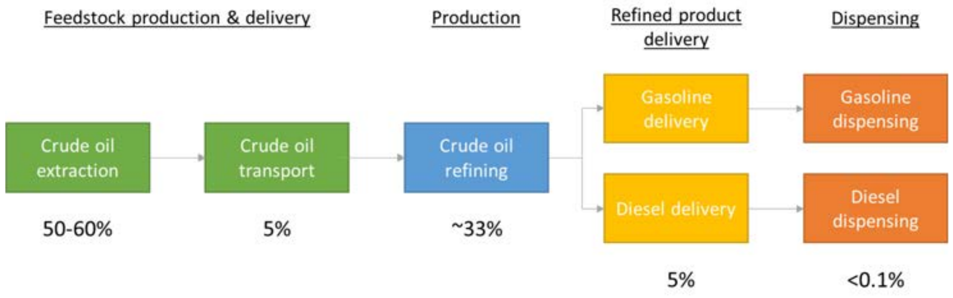
Trends and determinants of well-to-tank greenhouse gas emissions

Oil products

Crude oil extraction requires energy to power drilling rigs, pumps and other auxiliary equipment, which varies regionally for different types of oil production. Oil production can be classified into several categories, or stages. In the primary recovery stage, oil flows to the surface through natural pressure in the reservoir. As pressure in the reservoir decreases, oil production rates fall. To increase pressure in the reservoir and extract more viscous oil, water or gas is injected into the well during the secondary recovery stage. Remaining oil can be extracted in the tertiary stage, enhanced oil recovery, when CO_2, steam or other chemicals are injected into the reservoir. Heavy oil production generally requires enhanced oil recovery from the beginning of extraction.

The use of more energy-intensive extraction methods such as enhanced oil recovery can push up the carbon intensity of oil production – the greenhouse gas emissions per unit of energy (gCO_2-eq per megajoule) incurred during a given process or stage of the well-to-tank system boundary. Countries where energy-intensive methods are used to extract oil (e.g. thermal enhanced oil recovery) have high oil extraction carbon intensities. Using captured and stored atmospheric CO_2 for enhanced oil recovery could reduce emissions, but the majority of enhanced oil recovery projects inject CO_2 sourced from underground deposits.

Well-to-tank system boundaries of refined oil products



Note: Representative shares of well-to-tank emissions for each process refer to 2019.

A study of the greenhouse gas emissions incurred in oil production found that on average, CO_2 contributes 65% and methane 34% of greenhouse gas emissions from "upstream" processes – the exploration, drilling and development, production and extraction, surface processing, and transport to the site of refining – and that these emissions accounted for 5% of total global fuel combustion emissions in 2015.

Overall, greenhouse gas emissions associated with the energy used for oil production represent about 15% of well-to-tank emissions. In addition, CO_2 may be emitted when gas is flared or methane escapes as fugitive or vented emissions. Together, such emissions can constitute around 40% of well-to-tank greenhouse gas emissions for providing oil-derived gasoline and diesel.

Crude oil is mostly transported via pipelines and ships. A variety of fuels can be used to power the pumps and heaters sometimes needed for pipeline transport, while crude oil tankers are powered by heavy fuel oil. Crude oil transport represents around 5% of total well-to-tank emissions.

Overall, refining typically represents around one-third of the well-to-tank emissions of oil products. Refining starts with separation of crude oil into various hydrocarbon fractions (crude distillation). Complex refineries add a step to convert low-value fractions into high-value ones (upgrading). Emissions from condensate splitters and natural gas liquids fractionation plants were also considered in the assessment although these units mostly produce lighter products – such as ethane, liquefied petroleum gas (LPG) and naphtha – rather than conventional road transport fuels. Refining emissions are then allocated among the final products – including gasoline, diesel and kerosene – according to the processes required to produce each product. For example, the well-to-tank emissions of gasoline are higher than those of diesel, reflecting the more energy-intensive refining process units (e.g. hydrocracking) used to produce gasoline products.

Refining emissions are influenced by a range of factors, including i) refining activities; ii) refinery configurations; iii) type of crude oil; iv) type of energy sources used in operation; v) efficiency improvements; and (vi) hydrogen supply (for further details, see Annex 1 and World Energy Outlook 2018). The type or quality of crude oil influences the level of processing required and thus the configuration and complexity of the refinery. More complex refinery configurations are needed to process high-density (heavy) and high-sulphur (sour) crude into petroleum products, than low-density (light), low-sulphur (sweet) crudes. More complex refineries are also needed to upgrade lower-value petroleum products to higher-value products and for hydrotreating to remove contaminants, which are the largest source of refinery emissions. Hydrogen for hydrotreating is typically produced via steam methane reforming, which results in significant emissions unless equipped with carbon, capture, utilisation and storage (CCUS).[1]

While it is not the dominant energy source, the combustion of petroleum coke, a residue produced from refining heavy crude oil, to fuel refinery processes is also emissions-intensive, accounting for over 15% of refinery emissions globally.

Variability and opportunities to reduce greenhouse gas emissions

Regional variability in the emissions intensity of gasoline and diesel production stems from several factors, including refinery complexity, trade flows and the type of crude oil resources. For example,

[1] Indeed, a key factor driving the energy intensity of refinery operations is the hydrogen content of the products in relation to the hydrogen content of the crude.

extracting and processing oil from tar sands or extra-heavy oil produces distillates with a high carbon intensity.

Currently, crudes originating in Asia (excluding the People's Republic of China, [hereafter, "China"]), Europe, the United States, Africa and Oceania have lower refining emissions because their quality is higher than that of crude produced in Canada and Latin America. Refineries that use hydrocracking and coking to refine heavy and sour crude dominate in China, India and the United States. Less complex refineries treating sweet to medium crudes and sour crudes dominate in Japan, Korea and the Russian Federation, resulting in lower carbon intensities. Chinese oil products have a high well-to-tank emissions intensity as petroleum coke is increasingly used in refineries.

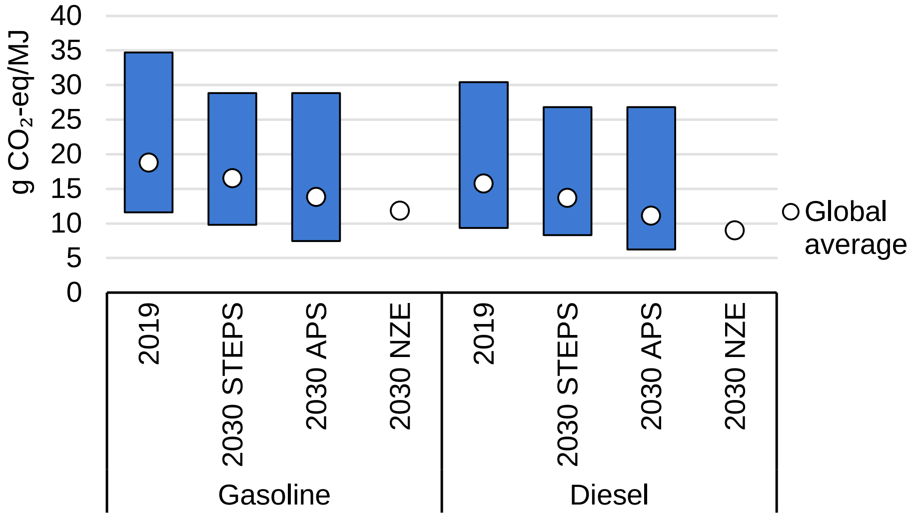
Improving energy efficiency and integrating renewable energy in oil production and refining can reduce well-to-tank emissions. Co-generation[2] technologies that capture and reuse waste heat can reduce refining emissions by more than 10%. In addition, low-carbon hydrogen – produced from steam methane reforming with CCUS, biomass or renewables-powered electrolysis – can be used to replace hydrogen produced through steam methane reforming without CCUS. Improving the energy efficiency of steam methane reforming would also reduce natural gas consumption and combustion emissions.

Emissions can also be reduced by installing CCUS at various refinery units and by switching fuels, for example by electrifying upstream processes. As these and other opportunities are taken up, well-to-tank emissions of refined oil products are expected to decrease from 2020 levels by around 15% by 2030 in the IEA Stated Policies Scenario and 40% in the IEA Announced Pledges Scenario.

In the Stated Policies Scenario, efficiency improvements are offset by the addition of upgrading and hydrotreating capacity to reduce yields of heavier oil products. In addition, more energy-intensive resources are exploited as current sources decline, though this is offset by using cost-effective technologies to reduce methane emissions. In the Announced Pledges Scenario, the primary driver of additional emissions reductions is the application of all available methane emissions reduction technologies in countries with climate pledges.

[2] Co-generation refers to the combined production of heat and power.

Regional variation of well-to-tank emissions intensity for gasoline and diesel, 2019 and 2030

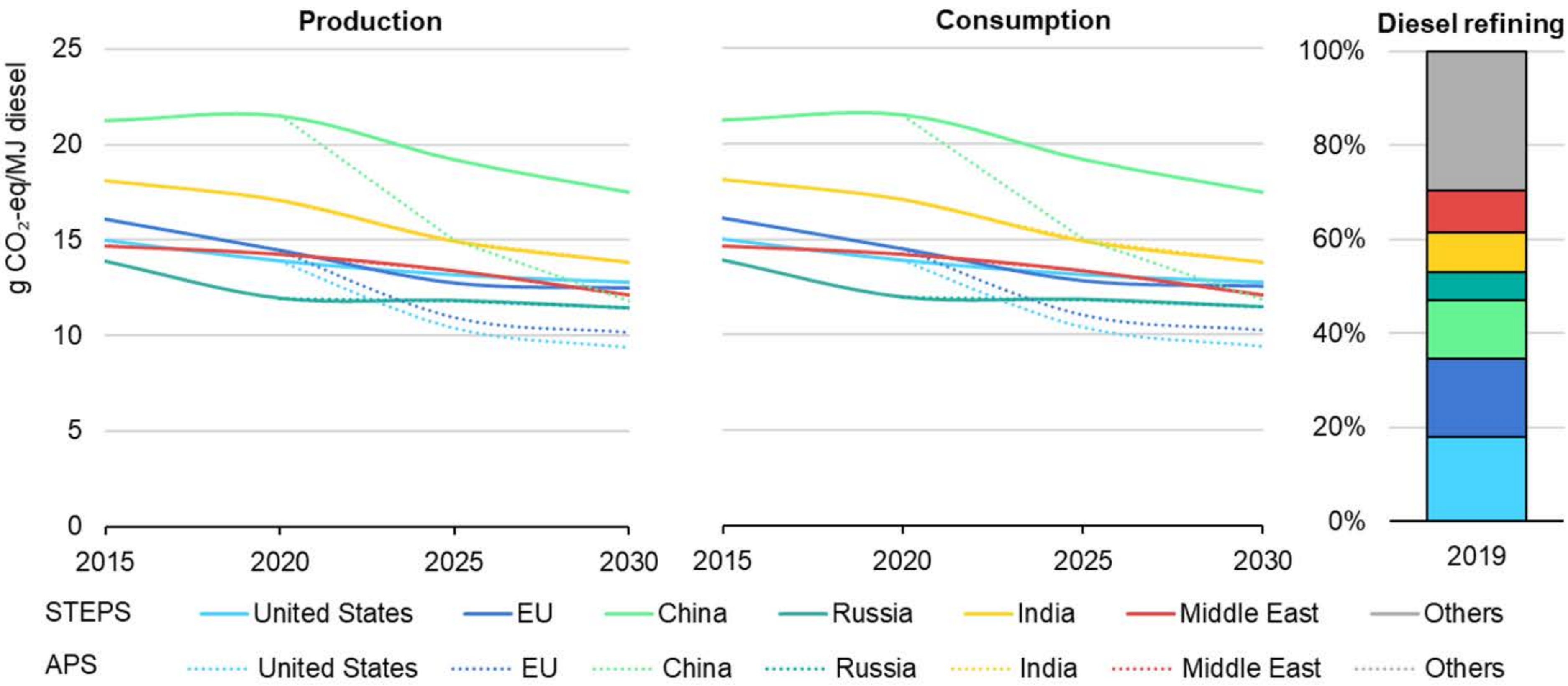


Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. The blue bars represent the variation of emissions intensity across IEA Mobility Model regions. Global averages are volume-weighted by country and regional production. Only the volume-weighted global average is shown for the Net Zero Emissions by 2050 Scenario.

Differences in the carbon intensity of oil products produced versus consumed across major gasoline- and diesel-consuming regions are minor. That is because major refining countries typically produce substantial shares of the crude that goes into their domestic refineries, and when crude is imported from other countries, that crude is of the quality required by those same domestic refineries.

Well-to-tank emissions of diesel from the perspective of the country of production and consumption

Well-to-tank emissions intensity of diesel, 2015-2030



Notes: Emissions factors from the consumption perspective differ from the production perspective based on historical and projected trade flows. The STEPS trajectory is the same as the APS for India.The bar chart indicates the share of diesel output from refineries by region.

Sources: IEA World Energy Outlook Model; IEA Mobility Model, August 2021 version.

Flaring, venting and fugitive emissions: Economic and regulatory considerations associated with natural gas and oil

Flaring is the intentional combustion of natural gas during oil and gas exploration, processing and production. Venting is the intentional release of natural gas directly into the atmosphere, and fugitive emissions are unintentional gas leaks and releases. Flaring is largely an economic decision influenced by physical and regulatory constraints. Capturing associated gas requires additional infrastructure beyond what is required for oil production. Most commonly, flaring occurs when the cost of building and maintaining the infrastructure and services required to bring gas to market is higher than the market value for gas. In these circumstances, producers may focus exclusively on oil extraction. Uncertainty about future gas demand and about the potential to extract natural gas from new wells sometimes leads producers to flare initially and leave open the option of building infrastructure later if market or technical certainty improves.

The latest IEA estimate is that 45% of methane leaks could be avoided at no net costm based on average natural gas prices from 2017-21.

Regulations have proved to be effective in reducing methane emissions from venting and flaring of natural gas. Regulations may include standards for measuring and reporting volumes of flared and vented gas and/or prohibiting unauthorised flaring and venting of associated gas. In addition, fiscal regulations in the form of incentives and penalties can help establish economic conditions that reduce emissions.

For instance, Norway has reduced flaring by 60% from pre-1990 levels by requiring producers to metre flared gas and by taxing flaring-related CO_2 emissions. Similarly, gas flaring declined by 70% from 1996 to 2004 in Canada, where regulations limit flaring volumes and require mandatory leak detection and equipment repair. In Nigeria, a combination of regulations and financial incentives facilitating investment in natural gas infrastructure has helped reduce flaring by 70% since 2000. In contrast, gas flaring increased by 13% between 2014 and 2019 in Iran, where there is limited enforcement of regulations on flaring and investments in natural gas infrastructure.

Since fugitive emissions from oil and gas are difficult to detect without the proper equipment, regulatory instruments that require continuous surveillance, inspection and leak repair are needed to reduce methane emissions. In Colorado, the number of fugitive methane leaks decreased by 52% in 2018 after 2014 regulations required detection and repair of such leaks. More recently, Canada introduced regulations for mandatory inspection and repair of fugitive methane leaks, as well as equipment standards. Among other policies, such regulations are expected to help Canada meet its target of reducing methane emissions from oil and gas by 40-45% by 2025.

Natural gas

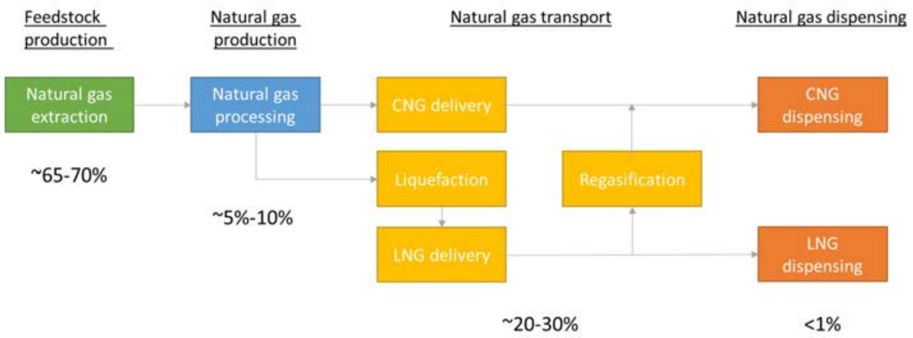
Dedicated natural gas production supply chains share many sources of energy consumption and upstream emissions with oil production. These include energy required for drilling equipment, maintaining reservoir pressure (and, in the case of hydraulic fracturing, powering fracking pumps) and powering auxiliary services. In contrast to oil extraction, however, gas flaring is negligible at dedicated natural gas extraction facilities.

Nevertheless, equipment leaks, vents and removal of liquid build-up in the gas well are a source of methane emissions during gas extraction. Emissions intensity estimates vary substantially due to differences in the age of wells and equipment, and in operating procedures. Natural gas extraction contributes about two-thirds of well-to-tank emissions from natural gas supply.

Another difference from oil is that natural gas processing may require removal of impurities such as CO_2, hydrogen sulphide or sulphur dioxide. Natural gas deposits can contain large amounts of CO_2 – even up to 90% – which, for technical reasons, must be removed before the gas is sold or processed to produce liquefied natural gas (LNG). The CO_2 is typically removed at the sulphur recovery unit of the processing plant.

The CO_2 removed is often vented into the atmosphere, which constitutes a little over 5% of well-to-tank emissions of natural gas. Alternatively, the CO_2 can be captured and reinjected into geological formations, either for permanent storage or for enhanced oil recovery. CCUS-equipped processing plants reduce the emissions intensity of natural gas/LNG supply. However, this does not avoid carbon emissions during end-use combustion, which would require further carbon management solutions, such as equipping power plants or hydrogen production facilities with CCUS. Twelve natural gas processing plants equipped with CCUS are operating today, with another five in various stages of planning.

Well-to-tank system boundaries of natural gas



Note: Representative shares of well-to-tank emissions for each process refer to 2019.

During natural gas delivery, methane is emitted (either unintentionally as fugitive emissions or intentionally vented for safety and to regulate pressure) at pipeline compressors, which themselves are powered by either natural gas or electricity. Transporting natural gas as LNG also involves liquefaction, which can be energy-intensive. During shipping of LNG, some small "boil- off" losses occur and some of the LNG cargo is used to fuel the LNG tanker. Taking into account the energy needed both to liquefy natural gas and to turn LNG back into gas, around 11% of the gas originally arriving at the liquefaction terminal is consumed.

Wide differences in emissions estimates can arise from poor accounting of methane emissions in venting and leaks, and because delivery pathways vary, including distances transported by pipeline or tanker and, for shipping, the size and efficiency of the tanker. Natural gas transport represents about a quarter of well-to-tank emissions.

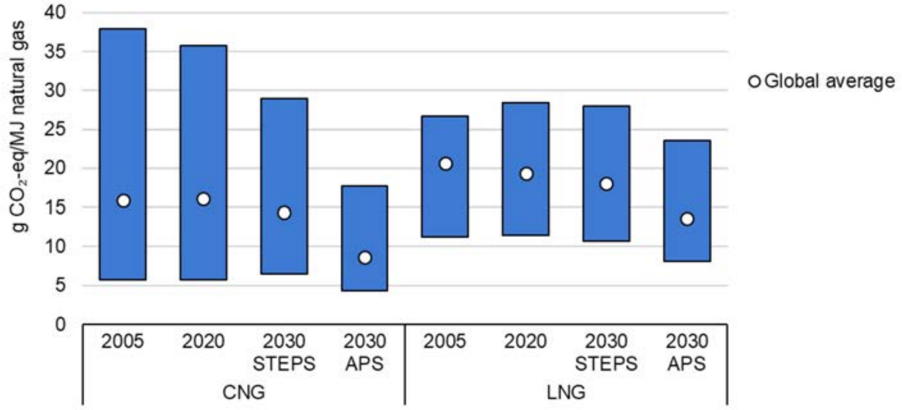
Variability and opportunities to reduce greenhouse gas emissions

Regional variations in emissions from gas production stem from several factors, including production technologies, the geology of the formations containing the gas, the composition of the extracted gas, the cost and application of emissions reduction technologies, and trade flows. When natural gas is liquefied for transport, the location of liquefaction facilities can also lead to regional variations in emissions, since ambient temperature affects the energy required for cooling.

The main opportunities to reduce methane emissions of natural gas are in the extraction and transport stages of the supply chain, which together constitute about 60% of well-to-tank emissions.

In the Stated Policies Scenario, it is assumed that methane emissions reduction measures that are currently cost-effective are employed, such as leak detection and repair. In the Announced Pledges Scenario, countries or regions committed to meeting climate targets are assumed to deploy all technology options to reduce methane emissions, regardless of whether the value of the captured methane is sufficient to cover the cost of the abatement measure. Under these assumptions, the well-to-tank emissions of natural gas are reduced by 10% by 2030 in the Stated Policies Scenario and by almost 50% in the Announced Pledges Scenario.

Regional variation of well-to-tank emissions intensity for compressed and liquefied natural gas, 2020 and 2030



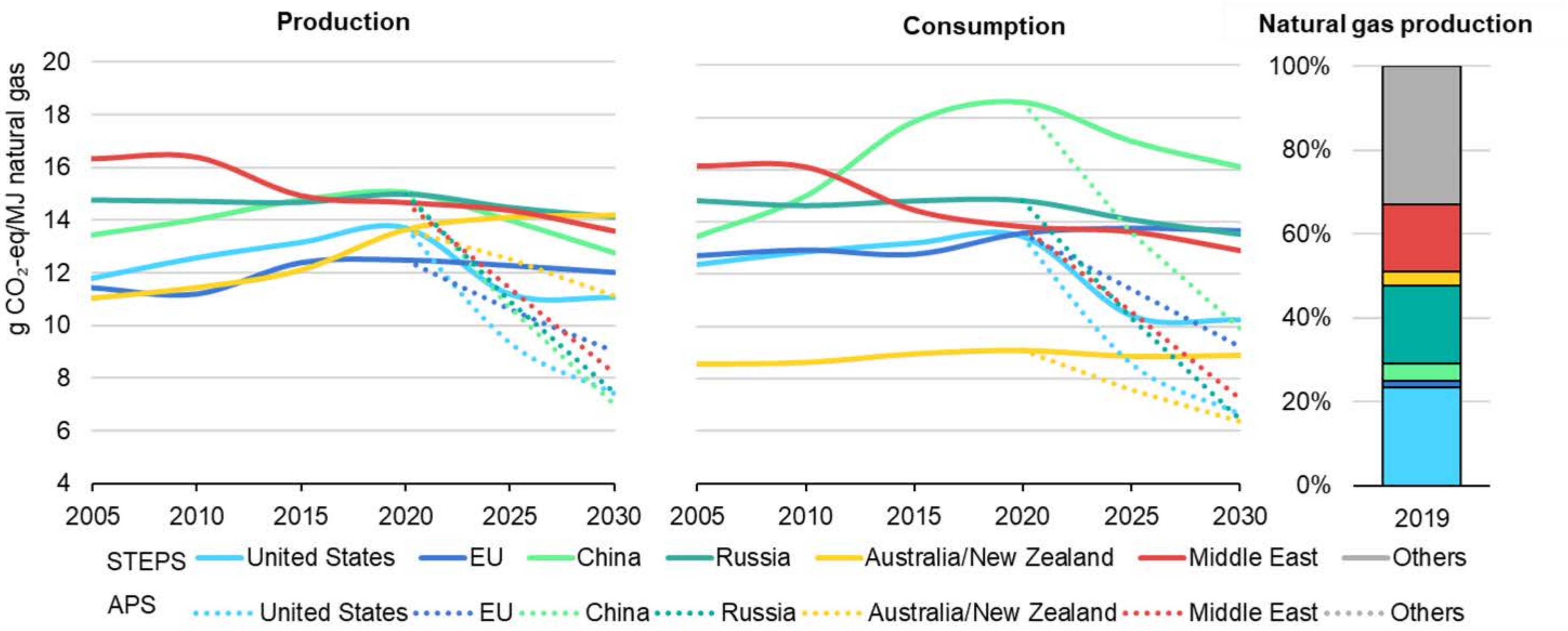
Notes: CNG emissions factors include gas liquefied for transport and then regasified for consumption. The blue bars represent the variation of emissions intensity across IEA Mobility Model regions and do not reflect country-level variability. In reality, LNG supply chains can reach emissions intensities higher than CNG, but this is not captured in the aggregated results shown in the figure.

Well-to-tank carbon intensity reductions come in large part from adopting best practices (including capturing fugitive emissions) and from technologies already in use for extraction, processing and natural gas transport. Methane emissions reduction measures constitute the majority of the reduction opportunities in the Announced Pledges Scenario but not in the Stated Policies Scenario.

Trade flows affect the emissions intensity of natural gas, and depend on the originating country's production and transport emissions. For example, natural gas production in Australia and New Zealand include the emissions intensity of exports, which incur higher emissions than domestically produced and consumed natural gas because of the longer transport distance. As a result, the carbon intensity of natural gas consumed domestically is lower than that produced because very little is imported from other countries. The well-to-tank emissions intensity of natural gas produced in Australia and New Zealand also increases in the Stated Policies Scenario as exports rise. A similar trend can be seen in the United States between 2025 and 2030 in the Stated Policies Scenario, where the emissions factor of domestically produced natural gas increases because exports increase. In contrast, the well-to-tank greenhouse gas emissions of natural gas consumed in China have increased over the last 15 years as imports from countries in the Caspian region have increased.

Well-to-tank emissions of natural gas from the perspective of country of production and consumption

Well-to-tank emissions intensity of natural gas, 2005-2030



Note: Emissions factors from the consumption perspective differ from the production perspective based on historical and projected trade flows. The bar chart indicates the share of natural gas production by region.

Sources: IEA World Energy Outlook Model; IEA Mobility Model, August 2021 version.

Biofuels

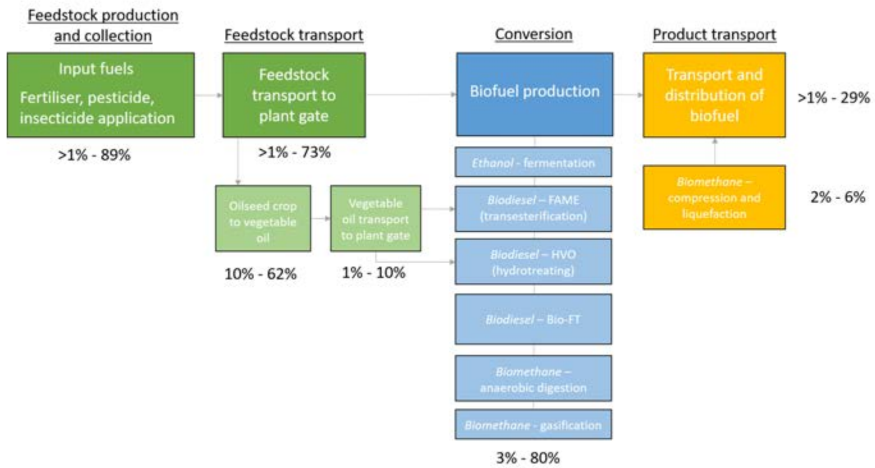
Biofuels are solid, liquid or gaseous fuels produced from the conversion of biomass – such as crops or waste – via biochemical, chemical and/or thermochemical processes. Biofuels are typically blended with (or in certain instances can fully substitute) fossil gasoline, diesel or natural gas in vehicles. Emissions reductions vary substantially depending on the feedstock and biofuel production process. The IEA Mobility Model covers 16 different feedstocks (including conventional food crops, agricultural and forest waste, and non-food energy crops), feeding into six biofuels production processes (ten including CCUS), resulting in 24 pathways (40 with CCUS).

The cultivation and harvesting of some feedstocks is more energy- and emissions-intensive than others. For example, food crop-based feedstocks (e.g. corn, sugar cane, palm, soybean) and energy crop-based feedstocks (e.g. switchgrass and miscanthus) require higher levels of fertiliser, insecticides and pesticides than waste-based feedstocks (e.g. forest residues and municipal solid waste) which require minimal or no such inputs.

In the case of food and energy crops, application of fertiliser, insecticides and pesticides can account for almost 20% to more than 80% of biofuel well-to-tank emissions. Agricultural or dedicated energy feedstocks are often tilled, irrigated and harvested by diesel, natural gas and/or electric-powered agricultural equipment, and contribute from 3% of well-to-tank emissions (in the case of canola oil-based hydrotreated vegetable oil [HVO]) to 26% (in the case of sweet sorghum ethanol).

Feedstock collection, field treatment, handling, drying, processing and storage require additional energy, primarily supplied by diesel. Post-harvest processing generally involves preparing and drying wet feedstock to minimise moisture content and to reduce weight and volume for transport from farm to the biorefinery.

Shares of well-to-tank emissions from biofuel pathways



Notes: FAME = fatty acid methyl ester; bio-FT = biomass gasification and Fischer-Tropsch synthesis. Biomethane from anaerobic digestion has not been included due to the complex calculation from its counterfactual case.

Feedstocks are generally transported from farms to biorefineries (or other conversion sites) by diesel truck, with emissions varying widely depending on the energy density of the processed feedstock and the distance travelled.

Feedstocks are generally trucked directly to either the biorefinery or first to a mill (for vegetable oil extraction) and then to the biorefinery. Typical distances assumed in GREET range from around 20 km to 140 km, depending on the feedstock. For example, forest residues require larger ranges for collection and hence are assumed to travel greater distances, while sugar cane is assumed to grow closer to the biorefinery.

From the biorefinery, the finished biofuel is generally transported to a bulk terminal. Depending on the location of the biorefinery and its end market, the transport mode and distance can vary significantly. For closer-range transport (320 km-1300 km), truck, barge, pipeline or rail can be used. For longer-distance transport (15 000 km-19 000 km), the fuel is taken by ocean tanker to another bulk terminal (often in another country). The biofuel is then typically blended at the final bulk terminal (with gasoline or diesel, for example) and the blended fuel trucked to a refuelling and dispensing station (50 km on average). As these distances were taken from GREET, they are largely representative of US markets (see Annex 2).

Collectively, transport of the feedstock to plant gate and of the finished biofuel product can account for negligible shares of well-to-tank emissions – 2% in the case of grain sorghum ethanol – or as much as nearly 28% in the case of sugar cane ethanol transported by ship. In pathways with minimal or no farming emissions and low carbon intensity, such as biomass gasification followed by Fischer-Tropsch synthesis (bio-FT) from forestry residues, as much as 80% of the well-to-tank emissions come from transport, mainly from diesel consumption.

The conversion of feedstocks into biofuels can follow several pathways depending on the feedstock and end product.

Conventional ethanol is produced from sugar or starchy food crops (e.g. sugar cane, sugar beet, corn and cassava) and advanced or cellulosic ethanol is produced from woody (or cellulosic) feedstocks (e.g. crop residues, forestry residues, and energy crops such as poplar, willow and miscanthus). In both routes, biomass undergoes enzymatic fermentation to produce ethanol, emitting a pure stream of CO_2, offering an opportunity to install CCUS. The ethanol is then dehydrated and denatured. The only additional processing step required in cellulosic ethanol is the hydrolysis, or breaking down, of the feedstock to release sugars that are then fermented. In addition to ethanol, the fermentation process produces distillers grains that can be dried and sold as animal feed.

Biodiesels have several production routes available to them. This report uses the term “biodiesel” for all biomass-based diesel substitutes. The biofuels industry usually uses “biodiesel” to refer to FAME and “renewable diesel” to refer to drop-in fuels – fuels that can fully substitute for petroleum-based hydrocarbons – from HVO and bio-FT.

The first route utilises transesterification to FAME. Vegetable oils from oilseed food crops (e.g. palm, soybean, rapeseed) or energy crops (e.g. jatropha) are reacted with methanol to produce a mixture of biodiesel and glycerine. Waste oils from used cooking oils or animal fats can also undergo transesterification, though they require an additional esterification step to convert a greater portion of the feedstock into FAME.

The second route reacts oil feedstocks such as vegetable oils and waste oils with hydrogen in hydrotreating processes similar to those used at fossil oil refineries. The resulting mixture of hydrocarbons is sent to a distillation column for separation into light, gaseous components and HVO, also known as hydroprocessed esters and fatty acids (HEFA) or renewable diesel. HVO can fully substitute for fossil diesel, in contrast to FAME. HVO also has very low levels of aromatics, which are pollutants, and a high cetane number, which results in improved diesel engine performance.

The third biodiesel production route, bio-FT, can use woody feedstocks such as crop residues, forestry residues and certain energy crops (e.g. willow, poplar, switchgrass and miscanthus) to produce syngas, a mixture of carbon monoxide, CO_2 and hydrogen. The syngas flows to a water-gas shift reactor, and the resulting stream is stripped of CO_2 before undergoing the Fischer-Tropsch synthesis reaction to produce liquid hydrocarbons. A distillation unit then separates products into diesel, kerosene, naphtha and other fractions. Similar to HVO, bio-FT is considered a drop-in biofuel, and is also known as renewable diesel.

Biomethane can be produced via two main pathways. The first route includes the microbial anaerobic digestion of organic matter such as animal manure, crop residues or the organic fraction of municipal solid waste (also known as biogenic municipal solid waste). The digester produces raw biogas, which can then be upgraded to biomethane by removing CO_2 and other contaminants such as hydrogen sulphide. The second pathway takes woody feedstocks and submits them to biomass gasification, similar to the first step in bio-FT. In this case, the resulting syngas is then cleaned to remove CO_2 before reacting the carbon monoxide and hydrogen via methanation to produce biomethane (also known as bio-synthetic natural gas [bio-SNG]).

Biofuel conversion efficiencies (e.g. at biorefineries) assumed in Energy Technology Perspectives supply modelling can differ slightly from those adopted in GREET (for further details, see Annex 2). This is one of the reasons that the Stated Policies Scenario and Announced Pledges Scenario result in different well-to-tank factors compared with GREET results in 2020. Further differences are explained by regional variations in input fuels.

CCUS can be installed in biorefineries that produce a concentrated, pure stream of CO_2. These include all ethanol pathways, bio-FT and both biomethane pathways (anaerobic digestion and gasification). This CO_2 can either be permanently stored or used for other applications such as synthetic fuels production. Storing or using CO_2 waste streams may be particularly attractive as a way to reduce emissions intensities for biofuels pathways with higher well-to-tank factors such as starch ethanol. In pathways equipped with CCUS, any biogenic emissions from combustion in the biorefinery are assumed to be offset by the CO_2 absorbed from the atmosphere during the growth of the biomass. Accounting for biogenic emissions from the combustion of the biofuel within a vehicle (tank-to-wheel) follow a similar concept (see Annex 2).

Variability across and within biofuels pathways

Within a given technology, the type of feedstock drives most of the variability in well-to-tank carbon intensity. Regional variability in the carbon intensity of biofuels pathways can be attributed to the mix and carbon intensity of input fuels used in both farming and conversion processes (see Annex 2). The figure below includes the well-to-tank carbon intensity values both excluding the biogenic carbon sequestered in the feedstock (white dots and blue range bars) and including it (orange dots). This aims to distinguish the well-to-tank emissions incurred from the potential to sequester CO_2 in the feedstock (which is later released again to the atmosphere when combusted in vehicle engines). The projected carbon intensity of feedstock-conversion pathways in 2030 is included in the Stated Policies Scenario and the Announced Pledges Scenario (see Annex 2).

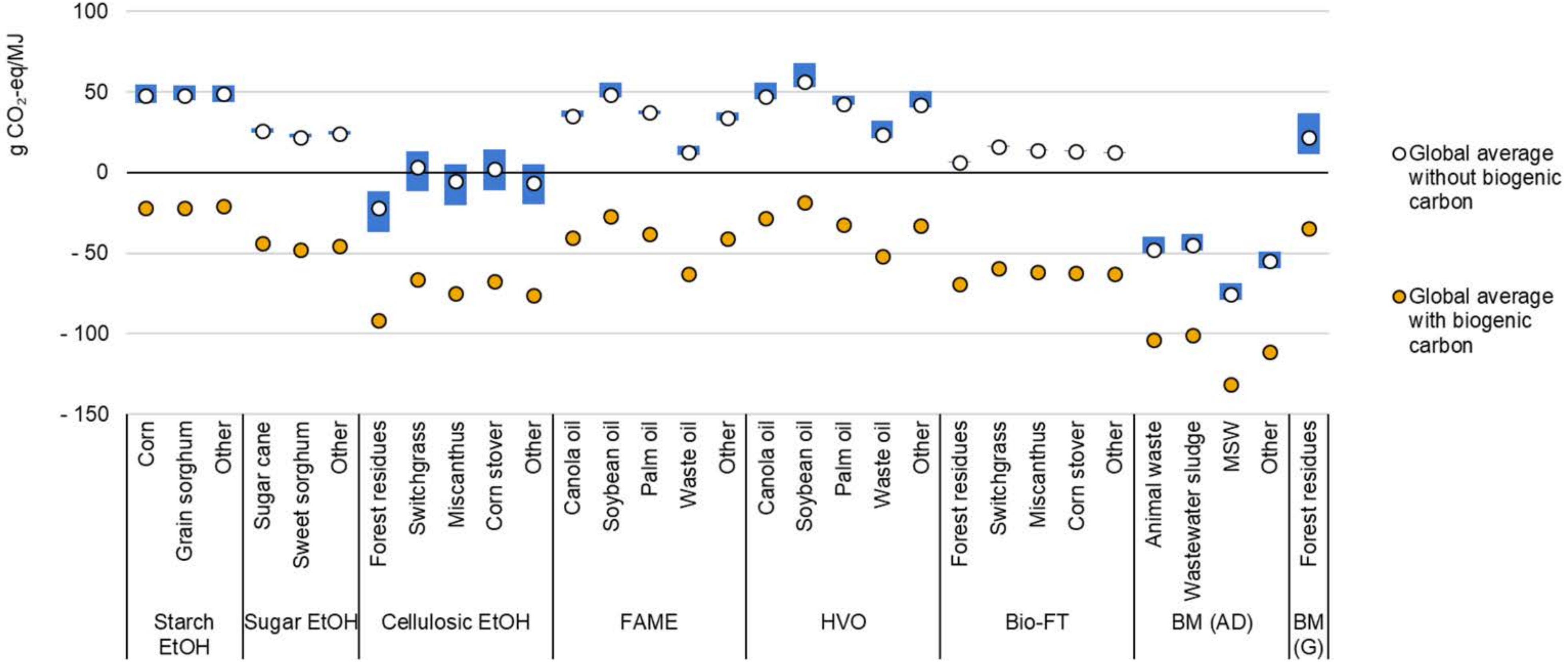
Emissions intensities vary considerably across the ethanol pathways, which include starch-based, sugar-based and cellulosic ethanols. Starch-based ethanol pathways are on the higher end of the ethanol emissions intensity range, with a global volume-weighted well-to-tank average of 48 g CO_2-eq/MJ in 2020. This can be attributed to emissions incurred by the fuels that power conversion at the biorefinery (including non-biogenic fuels such as natural gas, coal and electricity). These account for up to 55% of well-to-tank emissions. In contrast, conversion processes for sugar-based ethanols can use residual feedstock products (such as sugar cane bagasse), with minimal fossil fuel inputs, accounting for 3-11% of well-to-tank emissions. In the case of cellulosic ethanol, an electricity credit is allocated for the additional power produced from biomass combustion. This credit offsets the emissions incurred by grid electricity based on the carbon intensity of electricity production, resulting in negative emissions intensities attributed to cellulosic feedstocks. Countries with higher-intensity grids benefit from larger credits as the differential between the grid electricity carbon intensity and the biomass carbon intensity is greater. This credit declines as the carbon intensity of the grid falls. In the Stated Policies Scenario and the Announced Pledges Scenario it falls from -11 g CO_2-eq/MJ in 2020 to -7 g CO_2-eq/MJ in 2030.

In the short term, the electricity credit applied in 2020 has a small impact on total well-to-tank carbon intensity, as minimal cellulosic ethanol is produced. Waste-based ethanol feedstocks such as forest residues have even lower emissions intensities, as upstream emissions from feedstock collection and drying are minimal.

Emissions intensities vary widely also for biodiesel technologies, including FAME, HVO and bio-FT processes. For FAME, most virgin vegetable oil well-to-tank emissions arise from farming and from vegetable oil extraction from the oilseed crop (50-88%). Emissions from HVO processes are generally 12-30% higher than from FAME processes, except in the case of waste oil, where the emissions intensity is double that of FAME (with a volume-weighted global average of about 23 g CO_2-eq/MJ). Variations in the carbon intensity of hydrogen used for hydrotreating of vegetable oil reflect steam methane reforming hydrogen production.

Well-to-tank carbon intensity of biofuels pathways is largely determined by the feedstock used

Regional variation and global average carbon intensity across feedstock specific biofuel pathways in 2020



Notes: EtOH = ethanol; BM= biomethane; AD = anaerobic digestion; MSW = municipal solid waste; G = gasification. Biodiesel pathways: FAME, HVO, bio-FT. The blue bars represent variability across IEA Mobility Model regions, and include all the emissions incurred in cultivating, processing and transporting feedstocks, and then converting them to and transporting biofuels, but excludes biogenic carbon sequestered in the feedstocks. The orange dots include the carbon sequestered in the feedstocks. The global average is the non-volume-weighted average across all regions.

Source: IEA Mobility Model, August 2021 version.

For palm oil-based FAME and HVO, methane emitted from palm oil mill effluent at open pit palm mills – the vast majority of palm oil mills – makes up 40-50% of total well-to-tank emissions.

The least carbon-intensive technology for producing biodiesel is bio-FT, with well-to-tank carbon intensities of 6 g CO_2-eq/MJ to 16 g CO_2-eq/MJ. This is largely due to the use of more waste-based feedstocks, such as forest residues or corn stover, but also because bio-FT biorefinery emissions are low. Gasification of biomass produces sufficient off-gases that can be used to heat the thermochemical reaction that takes place, and hence no additional fossil fuels are needed in biomass conversion. Where energy crops are used, nearly all of the bio-FT emissions come from cultivation, harvesting and feedstock collection.

Currently, the vast majority of biomethane is produced via anaerobic digestion, which is more commercially mature than gasification technologies.

Anaerobic digestion pathways show a smaller variance in the range of well-to-tank factors despite using a wide range of feedstocks. The emissions intensities of anaerobic digestion pathways are mostly negative, as these pathways benefit from a counterfactual case for the methane emissions that would have occurred if the feedstock had not been converted into biomethane or fertiliser and grid-electricity-offsetting credits (e.g. for animal waste). Fugitive methane emissions released during the anaerobic digestion or other methane leaks during transport were also included, contributing around 27 g CO_2-eq/MJ to almost 50 g CO_2-eq/MJ depending on the feedstock. Since the biomethane from gasification pathway does not benefit from such credits, the majority of emissions (40-80%) come from electricity and LPG inputs for biomass conversion within the biorefinery.

Direct and indirect land-use changes from cultivating different feedstocks vary significantly. When these additional impacts are added to the direct carbon intensities, the estimated carbon intensity of some pathways can be significantly greater than fossil gasoline, diesel or natural gas.

Direct and indirect land-use change emission factors

Biofuel	Emissions intensity Share, 2019
Conventional ethanol	
Corn	14 g CO_2-eq/MJ 48%
Sugar cane	17 g CO_2-eq/MJ 28%
Cellulosic ethanol/Bio-FT	
Corn stover	-0.6 g CO_2-eq/MJ 22%
Forest residues	17 g CO_2-eq/MJ 78%

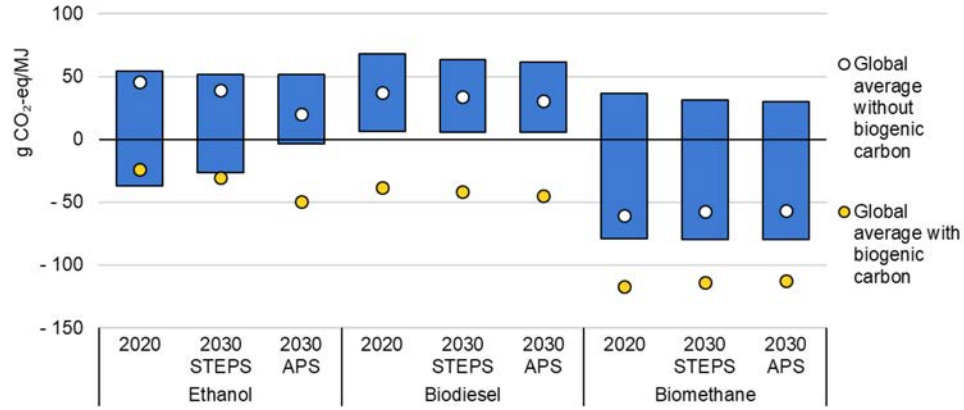
Biofuel	Emissions intensity Share, 2019
Conventional ethanol	
Miscanthus/switchgrass	-2.9 - 12 g CO_2-eq/MJ
Biodiesel (FAME/HVO)	
Palm oil	231 g CO_2-eq/MJ 58%
Canola oil	65 g CO_2-eq/MJ
Soybean oil	150 g CO_2-eq/MJ

Source: Valin et. al (2015), GLOBIOM and Argonne National Laboratory (2020), GREET CCLUB Module Revision 6.

Opportunities to reduce greenhouse gas emissions

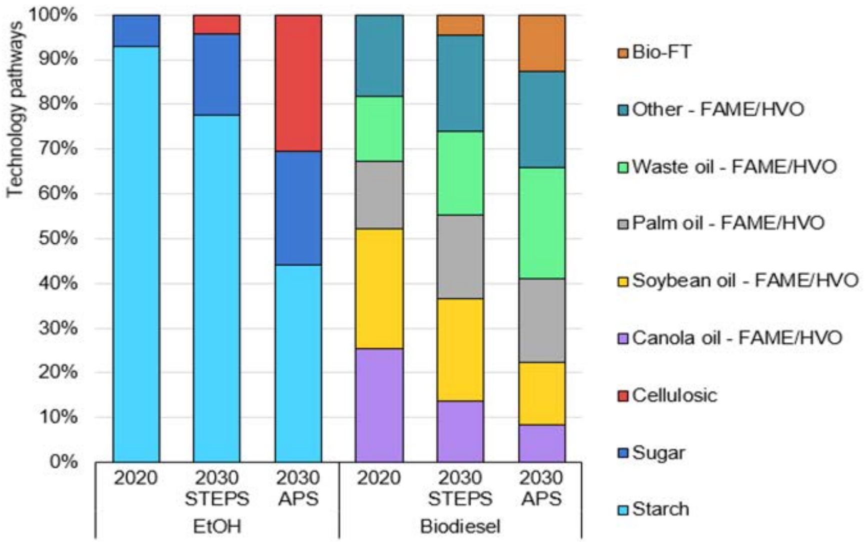
In both the Stated Policies Scenario and the Announced Pledges Scenario, biofuels production shifts towards lower-carbon-intensity feedstocks and conversion technologies. Biofuels conversion processes also rely on lower-carbon-intensity fuels, and become more and more efficient over time, with far greater efficiency potential than in pre-commercial conversion technologies. These shifts are more rapid in the Announced Pledges Scenario, reflecting increased policy focus on driving down the greenhouse gas emissions incurred in biofuels production, and greater investment in low-carbon production pathways at all levels of technology development.

Regional well-to-tank variation and global average carbon intensity across biofuel pathways, 2020 and 2030



Starch- and sugar-based ethanol production, which currently collectively make up nearly all of global production, shift to cellulosic ethanol, which makes up less than 1% of ethanol production in 2020 and 30% of production in the Announced Pledges Scenario in 2030. The result is a 15% reduction in the global average well-to-tank emissions factor from 46 g CO_2-eq/MJ in 2020 to 39 g CO_2-eq/MJ in the Stated Policies Scenario and a 56% decrease to 20 g CO_2-eq/MJ in the Announced Pledges Scenario in 2030.

Biofuels feedstock supply breakdown, 2020 and 2030



Note: EtOH = ethanol.

In the case of biodiesel production, the shift is not as pronounced. Despite levels of advanced biodiesel (such as HVO or bio-FT) increasing considerably from 2% in 2020 to 22% in the Stated Policies Scenario by 2030 and 47% in the Announced Pledges Scenario by 2030, it is still largely dominated by HVO (80% of advanced biodiesel in the Stated Policies Scenario and 73% in the Announced Pledges Scenario), which has similar if not slightly higher carbon intensity compared to FAME biodiesel from the same feedstock. Despite faster acceleration of waste oil-based feedstocks for HVO, virgin vegetable oils still play a large role up to 2030. For example, large biodiesel-producing countries such as Indonesia that do not take carbon intensity into account in biofuels production (e.g. through regulatory mechanisms) still use a considerable amount of palm oil in the Announced Pledges Scenario 2030. Therefore this resulted in changes to the global volume-weighted averages for biodiesel from 36 g CO_2-eq/MJ in 2020 to 34 g CO_2-eq/MJ in the Stated Policies Scenario and 30 g CO_2-eq/MJ Announced Pledges Scenario.

Commercial technologies such as starch- and sugar-based ethanols, FAME, HVO and biomethane from anaerobic digestion are expected to undergo marginal efficiency improvements. Conversely, the potential for efficiency gains in pre-commercial technologies such as cellulosic ethanol conversion pathways, bio-FT and biomethane from gasification are substantial, as these technologies are currently at demonstration scale and lower deployment. As these technologies are deployed at larger scales, increased operational knowledge (e.g. handling diverse feedstocks, cleaning residues of dirt and debris) and learning-by-doing will improve efficiency.

For cellulosic ethanol, conversion yields improve by 15% between 2020 and 2030; for biomethane from gasification, conversion yields improve by 3% in that period; and bio-FT see 10% improvement between 2020 and 2030. For cellulosic ethanol, efficiency improvements peak in 2055 at 23% higher than in 2020, for bio-FT the improvement peaks at 15% above current levels by 2040, and for biomethane gasification improvements level off at 14% higher than current levels by 2050.

Electricity

Electricity has only recently begun to supply notable energy to power road transport, as battery and plug-in electric vehicles have begun to capture small but rapidly growing market shares.

Well-to-tank emissions from electricity include greenhouse gases emitted in producing and delivering primary resources (or feedstocks) used in the power plants, as well as emissions from generation, transmission and distribution, and from vehicle charging. Emissions incurred in building and maintaining infrastructure needed for each of these processes are not included in the analysis in this report.

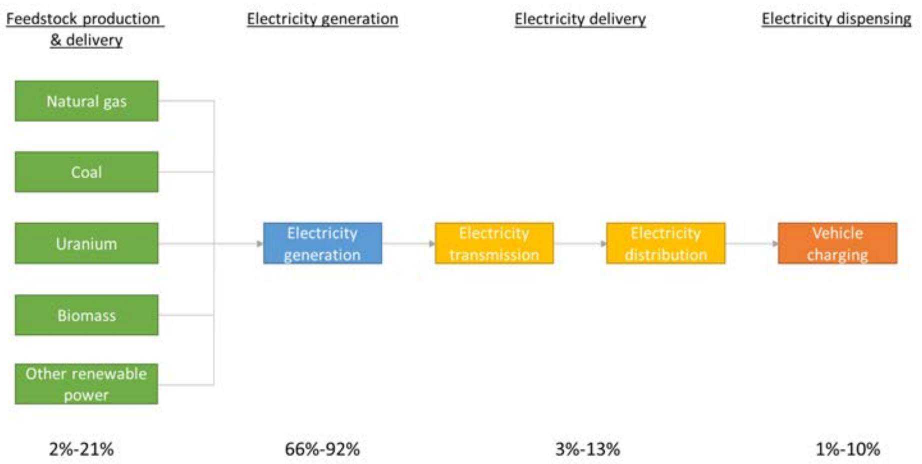
Feedstock production and delivery comprises extracting or producing the primary energy resources and their processing and transport. This stage accounts for less than 5% to 20% of well-to-tank emissions related to electricity, depending on the regional grid mix.[1]

Generation accounts for the majority of the well-to-tank emissions from electricity. Emissions intensities reported here are based on the annual average grid mix (i.e. shares of electricity generated), a method that is both simple and appropriate for estimating the emission impacts of electric vehicle charging in a global, long-term modelling tool such as the IEA Mobility Model.[2] The average, rather than the marginal greenhouse gas intensity of electricity generation is appropriate for a long-term scenario projection, as marginal decisions that affect investment and changes in the technology mix of electricity generation and storage are built into the modelling and should not be attributed to electric vehicle charging in the projections. However, annual average grid carbon intensity represents the weighted average mix of daytime and night-time charging, which does not necessarily correspond to how electric vehicles are actually charged (private cars are typically charged at night).

[1] In this analysis, upstream emissions are calculated only for natural gas, oil, coal, biomass and uranium inputs into power generation. Other renewable power generation (e.g. solar, wind, geothermal, etc.) is assumed to produce no upstream emissions.

[2] Alternative methodologies seek to estimate the emissions associated with the real-time mix during periods when vehicles are charging, or to estimate the fuel and technology that is being added to the generation mix to provide the next marginal unit of electricity demand during charging.

Well-to-tank system boundaries for electricity



Note: The range of shares of well-to-tank emissions are based on the 2019 regional grid mixes.

Another limitation of applying national average carbon intensities to estimate the well-to-tank emissions from driving electric vehicles is the fact that electric vehicles tend to be concentrated in cities and regions that may rely on grid mixes markedly different from the national average. For instance, most electric vehicles operating in the United States are in California or the Northeast, both of which have less carbon-intensive grid mixes than the US national average. Similarly, depending on where they are charged, the well-to-tank emissions of electric vehicles operating in China decrease notably along a northeast to southwest gradient, reflecting higher shares of hydropower and other renewables in province-level generation mixes.

Power generation emissions depend mainly on the fuel used to fire the power plant – each fuel has a specific carbon intensity – but also on the specific configuration and characteristics of the power plant. Pressure levels, use of CCUS, sulphur scrubbers and other pollutant reduction measures, type of cooling technologies, and the plant's age all affect its conversion efficiency.

Coal-fired power plants produced the largest share of electricity generated globally in 2019 – almost 40%. Electricity generated via coal-fired power plants tends to be the most carbon-intensive, largely due to the high CO_2 emissions factor of coal: around 100 g CO_2-eq/MJ on a higher heating value basis, with small variation across coal grades. The main determinant of the carbon intensity of the electricity generated via coal is the efficiency of conversion, which varies by type of coal-fired power plant.

Since natural gas has a lower CO_2 emissions intensity than coal (56 g CO_2-eq/MJ, higher heating value), and because the most commonly used gas turbine cycle – the combined cycle power plant (CCGT) – is more efficient than coal-fired power plants, the carbon intensity of gas-fired electricity generation is normally lower than that of coal-fired generation: around 360 g CO_2-eq/kWh for CCGT and 620 g CO_2-eq/kWh for open loop gas turbines.

Typical emission factors for fossil-fired power plants

Plant Type	Emissions intensity	Share, 2019
Coal 40%		
Subcritical	1 030–1 150 g CO_2-eq/kWh	48%
Supercritical	970–1 070 g CO_2-eq/kWh	28%
IGCC	890–990 g CO_2-eq/kWh	<1%
Ultra-supercritical	850–950 g CO_2-eq/kWh	25%
Natural gas 24%		
Open loop	~620 g CO_2-eq/kWh	22%
CCGT	~360 g CO_2-eq/kWh	78%
Heavy fuel oil 3%		
Open loop gas turbine	~860 g CO_2-eq/kWh	58%
Steam turbine	~760 g CO_2-eq/kWh	42%

Notes: IGCC = integrated gasification combined cycle. *Share, 2019* for a fuel indicates the estimated share of global electricity generation produced via plants powered by that fuel. Shares refer to generation of plants that produce electricity only, and do not include co-generation plants. For plant types, the value is the share of electricity generation from that plant type, within the total supplied by the fuel.

Electricity can also be produced via combustion of oil products, especially heavy fuel oil, or other non-renewable fuels. However, the use of these sources is gradually reducing globally, and in 2019 accounted for only 3% of electricity generation. As the greenhouse gas emissions intensity of heavy fuel oil – 77 g CO_2-eq/MJ, higher heating value – is between that of coal and gas, so too is the emissions intensity of plants using heavy fuel oil.

All fossil-fired power plants can be equipped with CCUS, which significantly reduces the carbon intensity.

Since nuclear power plants do not combust any fuel, the electricity generated is considered to be carbon-neutral. There are however emissions associated with the uranium mining. Greenhouse gas emissions embodied in the construction and operation of the plants falls outside the system boundary.

Collectively, renewables were the second-largest source of electricity generation – more than 25% – in 2019. They include mainly hydropower, solar photovoltaic, onshore and offshore wind turbines, geothermal, and biomass-fired electricity generation. In most cases, no fuel combustion processes are involved in generating renewable electricity and it is considered carbon-neutral.[3]

Between 5% and 15% of the total electricity generated is lost in the transmission and distribution of electricity to the point of use

[3] Emissions incurred in cultivating, harvesting and transporting biomass feedstocks are considered for biomass-fired electricity generation.

(charging stations, in the case of electric vehicles). These losses vary depending on the overall efficiency of the transmission and distribution networks and on the distance over which electricity is transmitted.

Finally, additional losses (with direct repercussions on well-to-tank emissions) occur during vehicle charging. These losses vary primarily depending on the power rating of the charger, with losses of around 5% incurred in case of slow charging (at a power rate below 22 kW), 10% for fast charging at 50 kW-150 kW, and more than 10% for ultrafast charging above 150 kW.

Variability and opportunities to reduce greenhouse gas emissions

In order of decreasing impact, differences in the well-to-tank greenhouse gas emissions intensity of electricity are attributable to differences in:

- **The composition of the power generation mix,** that is, the combination of fuels powering thermal power plants, as well as the share of renewable energy generation by type, used to generate electricity. For instance, well-to-tank emissions intensities are higher in regions that rely on coal for a high share of their power generation, such as Australia (58% in 2019), India (71%), and South Africa (88%). Conversely, renewable sources supplied 99% of the electricity generated in Norway in 2019, 100% in Iceland and 76% in Denmark.
- **Plant configuration and vintages** within each fuel category of fossil thermal power generation (and hence efficiency). For instance, while China still relied in 2019 on coal power to generate 66% of electricity, the average age of coal-fired powered plants was 12 years, and a high share (70%) of these were supercritical, ultra-supercritical or co-generation plants.
- **Distances and efficiencies** of electricity transmission and distribution. Losses can vary from less than 2% in a small, dense and technologically advanced country such as Singapore, to more than 30% in large, emerging market and developing countries. In advanced economies, transmission and distribution losses are typically around 6%

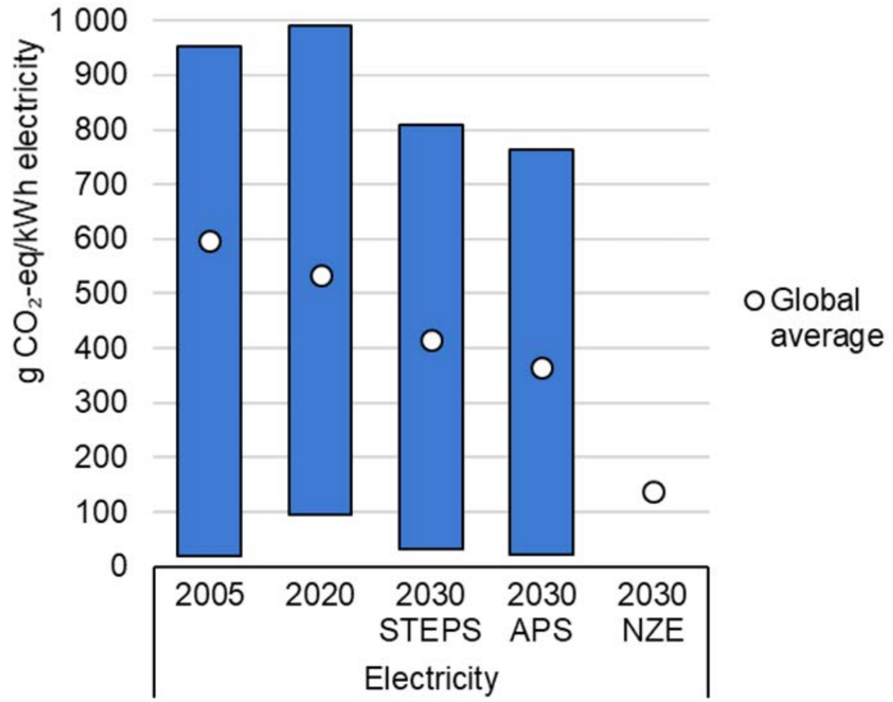
In 2020, the weighted average carbon intensity of final electricity worldwide is estimated to be 535 g CO_2-eq/kWh. This is over 10% less than in 2005, reflecting the continuing shift in power generation to lower-carbon and renewable sources.

Under current policy frameworks, the carbon intensity of electricity is expected to continue falling, reaching a global average of 415 g CO_2-eq/kWh in 2030 in the Stated Policies Scenario. Under the Announced Pledges Scenario, the global average well-to-tank emissions for electricity could fall further to 365 g CO_2-eq/kWh in 2030, assuming an acceleration in the pace of deployment of renewable and low-carbon power generation. In the Net Zero Emissions by 2050 Scenario, the global average well-to-tank emissions for electricity could even fall to 137 g CO_2-eq/kWh.

The reduction in carbon intensity at the global level over the coming decade reflects reductions in all regions. Despite regional differences in the pace of electricity decarbonisation, the general trend in both the Stated Policies Scenario and the Announced Pledges Scenario is a shift from carbon-intensive, fossil-fuelled generation to renewables, nuclear and other low-emission sources.

A key means of reducing emissions throughout the energy sector is the adoption of low-carbon electricity generation, coupled with electrification of end uses. This reflects the technical maturity and economic viability of renewables and other low-carbon electricity generation technologies, as well as the cost savings, efficiency and other shared benefits of electric end-use devices, including electric vehicles.

Regional variation of well-to-tank emissions intensity for electricity across Scenarios, 2005, 2020 and 2030

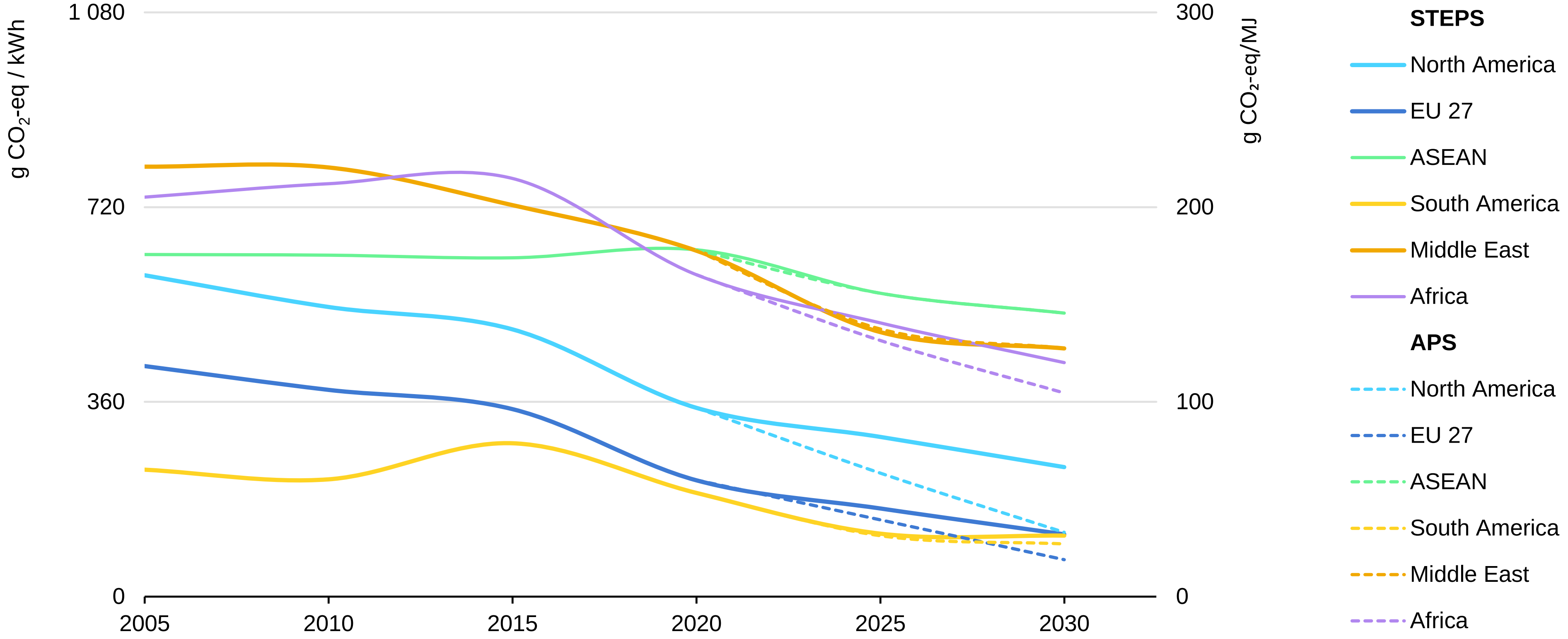


Notes: Well-to-tank emissions are for final electricity, i.e. they include transmission and distribution losses; upstream emissions related to the extraction, transformation and transport of the primary sources to the power plant; and charging losses (5%). Only production-weighted global average is shown for the Net Zero Emissions by 2050 Scenario.

Sources: IEA Energy Data Centre, IEA Energy Technology Perspectives Supply model, GREET model.

Emissions incurred in generating electricity have been gradually declining in most regions

Carbon intensity of electricity generation for selected regions, 2005-2030



Notes: ASEAN = Association of Southeast Asian Nations. North America includes Canada, Mexico and the United States. ASEAN includes ASEAN member countries. The well-to-tank emissions shown in the figure are for final electricity, i.e. they include transmission and distribution losses; upstream emissions related to the extraction, transformation and transport of fuels to the power plant; and charging losses (5%). The emissions trajectory for ASEAN is the same in STEPS as APS through 2030.

Sources: IEA Energy Data Centre, IEA Energy Technology Perspectives Supply model, GREET model.

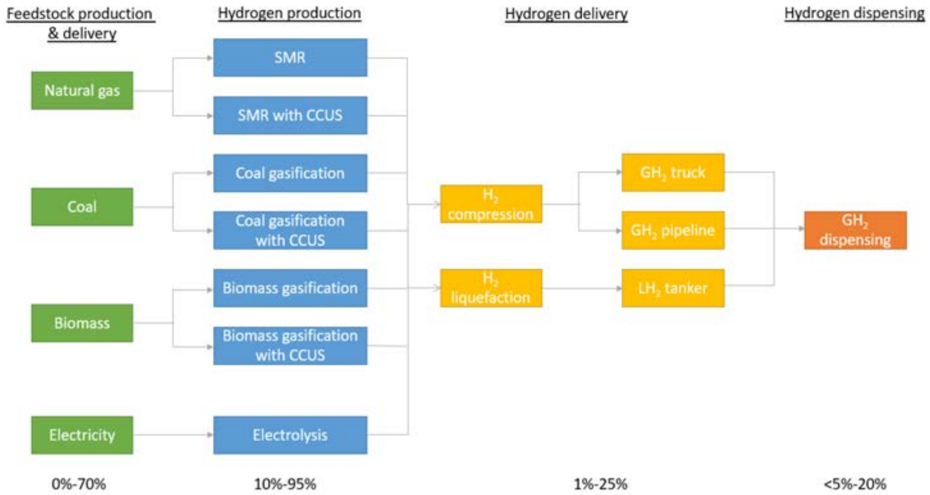
Hydrogen

The well-to-tank emissions associated with hydrogen are highly dependent on the feedstock used in hydrogen production. Most hydrogen today is produced via steam methane reforming of natural gas, or primarily in China, via coal gasification. Both of these pathways result in significant emissions during the hydrogen production phase, but the use of carbon capture, utilisation and storage (CCUS) can help mitigate these emissions.

For natural gas steam methane reforming, CCUS can reduce process emissions by about 90%, but requires about 10% higher natural gas consumption to power the unit. Even with CCUS, natural gas steam methane reforming is the most energy-efficient method for producing hydrogen (70% efficiency with CCUS, 76% efficiency without CCUS) though electrolysers may rival the efficiency of natural gas steam methane reforming in some cases.

The energy efficiency of the coal gasification process is around 60%, and well-to-tank emissions of hydrogen produced by coal gasification are about 60% higher than from natural gas steam methane reforming, due to higher emissions from the coal gasification process. For coal gasification, CCUS can reduce process emissions by about 85%, but requires 5% higher coal consumption.

Well-to-tank system boundaries of hydrogen



Notes: SMR = steam methane reforming; GH_2 = gaseous hydrogen; LH_2 = liquid hydrogen.

Biomass can also be gasified to produce hydrogen. Unlike coal, carbon uptake during biomass growth offsets biogenic emissions during gasification, resulting in net zero emissions (see Annex 2). As such, the majority of emissions for the biomass gasification pathway come from delivery and dispensing of the hydrogen. When coupled with CCUS, biomass gasification can result in net negative emissions, even though external electricity is assumed to power the CCUS unit. The energy efficiency of biomass gasification for hydrogen production is slightly lower than coal gasification, at about 55%.

Hydrogen can also be produced by splitting water molecules into diatomic hydrogen and oxygen using electrolysis. Low-temperature electrolysis, the process considered here, currently has an energy efficiency of about 65%. The well-to-tank emissions of electrolytic hydrogen production are determined by the source of electricity providing the energy. When grid electricity is used, the well-to-tank emissions can be high in regions that rely heavily on coal or natural gas for power production. However, electrolysis can also be paired with dedicated renewables, in which case well-to-tank emissions are solely from the delivery and dispensing of the hydrogen.

The distance and mode of hydrogen delivery influence energy consumption and associated emissions from this stage. Hydrogen pipelines are the least energy-intensive way to deliver hydrogen but are rarely used because demand is low and capital costs of new pipeline construction are high. Currently, hydrogen is mainly delivered by truck either in gaseous or liquid form, which results in tailpipe emissions and upstream emissions associated with the diesel used by the trucks delivering the hydrogen. Emissions are incurred in powering compressors to regulate the pressure at which gaseous hydrogen is transported, whether by pipeline or truck.

Liquefying hydrogen to enable greater quantities to be transported (which is more cost-effective in certain contexts) requires additional electricity, which reduces the energy efficiency of the pathway and results in emissions. In this analysis, it is assumed that grid electricity is used for liquefaction unless the hydrogen is produced from a renewable feedstock, in which case it is assumed that renewable electricity is used to maintain a low well-to-tank emissions factor.[1]

Finally, there are also emissions associated with the electricity that is required at hydrogen refuelling stations to run the compressors, refrigeration equipment and other components needed to dispense hydrogen into vehicles.

Variability and opportunities to reduce greenhouse gas emissions

Regional variations stem from regional differences in the upstream emissions intensity of energy feedstocks (e.g. natural gas and electricity) that are consumed in producing hydrogen. There are also variations in terms of which pathways are used to produce hydrogen in a region. At the global level, the majority of hydrogen is produced via natural gas steam methane reforming without CCUS (60%), though coal gasification also makes up a significant portion (almost 20%) and is especially prevalent in China. Transport constitutes just 0.02% of total hydrogen demand, but if fuel cell vehicles become more prevalent, policies promoting clean hydrogen production will be important to reduce emissions. For example,

[1] It is assumed that low-carbon hydrogen producers would either directly use renewable electricity for liquefaction or buy renewable electricity credits in order to maintain the low-carbon status. We are not considering international trade of hydrogen, thus the producing region is the same as the consuming region.

California, with one-third of the world's fuel cell electric cars, requires that at least 33% of the hydrogen dispensed by state-funded refuelling stations be renewable hydrogen. While the mix of pathways used to supply hydrogen for transport may differ from the overall supply mix, this analysis assumes the supply mix is used to fuel light-duty vehicles.

Electrolyser efficiency is expected to increase slightly (to 69%) as the technology matures, reducing well-to-tank emissions from electrolytic pathways. The largest contributor to well-to-tank emissions reductions, however, is decarbonisation of the grid mix. Lower-carbon grid electricity reduces emissions not only in grid electrolysis but in all pathways, given that electricity is used for compression, dispensing and other processes (including CCUS and liquefaction). Upstream emissions reductions related to natural gas also reduce the well-to-tank emissions of hydrogen produced by steam methane reforming.

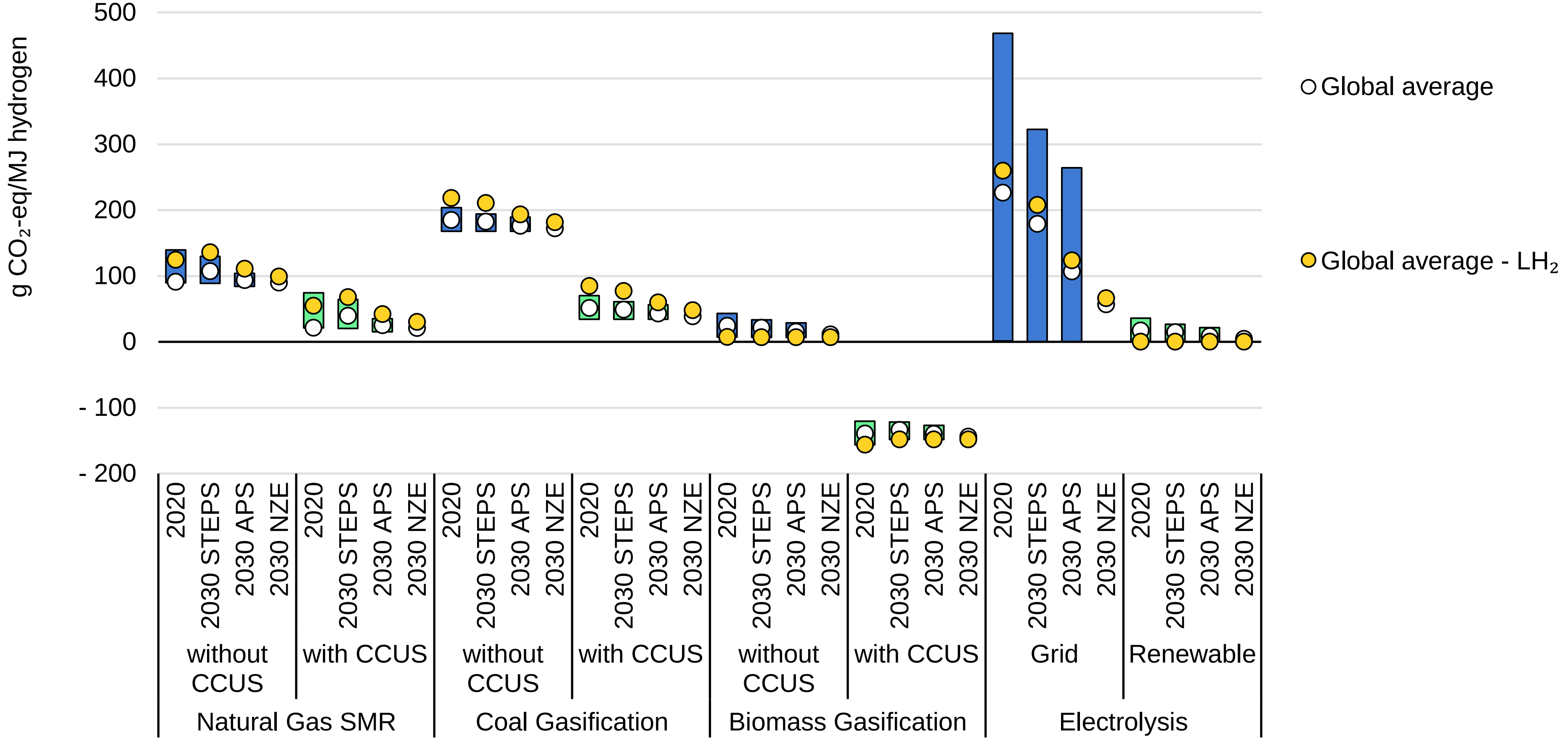
Given the efficiency losses at each step in the hydrogen supply chain, the carbon intensity of electrolytic hydrogen production relying on grid electricity is often higher than that of hydrogen production via steam methane reforming. When the carbon intensity of electricity generation exceeds 395 g CO_2-eq/kWh, it is higher even than that of coal gasification.

Hydrogen production from dedicated renewable electricity or biomass results in the lowest well-to-tank emissions, and when biomass gasification is coupled with CCUS it can sequester carbon.

In these pathways, liquefaction using renewables also has the potential to reduce well-to-tank emissions, as it reduces the energy required to deliver the hydrogen.

Well-to-tank emissions of hydrogen production pathways

Well-to-tank carbon intensity of hydrogen by technology pathway, 2020 and 2030



Notes: SMR = steam methane reforming; LH_2 = liquid hydrogen. The global averages are based on the global average emissions intensity of energy feedstocks (e.g. natural gas and grid electricity) and do not represent the hydrogen production weighted average. Global averages of the well-to-tank carbon intensity of compressed hydrogen and liquefied hydrogen incorporate GREET defaults on hydrogen delivery pathways, and so are not indicative of detailed global modelling of this stage of the supply chain, but nevertheless show the potential for additional well-to-tank emissions reductions through liquefaction in very low greenhouse gas pathways. Only global average is shown for the Net Zero Emissions by 2050 Scenario.

Sources: IEA Energy Data Centre, IEA Energy Technology Perspectives Supply model.

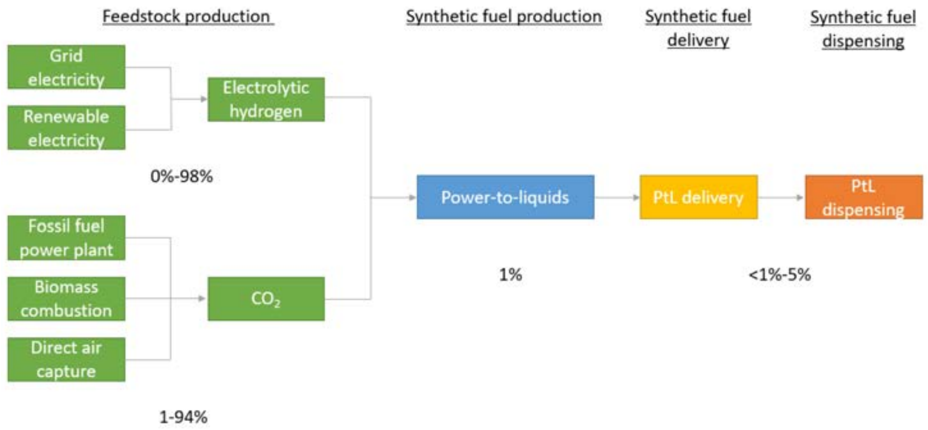
Synthetic fuels

In this report “synthetic fuels” refers to synthetic hydrocarbons produced using electrolytic hydrogen and CO_2 via a power-to-liquids process. The production of synthetic fuels requires either grid or renewable electricity to produce the hydrogen feedstock, as well as for the power-to-liquids process. The electrolysis process is the most energy-intensive phase of the supply chain, meaning use of grid or renewable electricity is the key determinant of well-to-tank emissions for synthetic fuels.

The CO_2 used can come from fossil sources such as coal or natural gas power plants, biogenic sources such as ethanol plants, or direct air capture. Whether the CO_2 comes from a concentrated source (e.g. a power plant or another industrial source, such as a steel production facility) or from direct air capture, the carbon capture process also requires electricity, though much less than what is required for electrolysis, as electrolytic hydrogen production constitutes over 90% of the electricity required to produce synthetic fuels. Regardless, the source of the CO_2 is the second-most-influential factor in determining well-to-tank emissions of synthetic fuels, as the CO_2 inputs from biogenic sources and direct air capture are considered negative since the CO_2 has been taken out of the atmosphere (see Annex 2).

The total energy efficiency for feedstock production (hydrogen and CO_2) and synthetic fuel production ranges from 46% for the pathways using fossil and biogenic CO_2 to 43% for pathways using direct air capture. Across all pathways, electrolytic hydrogen production is responsible for over 90% of the total electricity consumption. Additional energy is also required to deliver and dispense the synthetic fuel, though this has a negligible impact on total energy efficiency.

Well-to-tank system boundaries of synthetic fuels



Note: PtL = power-to-liquids.

The power-to-liquids process combines CO_2 and electrolytic hydrogen to produce synthetic hydrocarbons. The CO_2 and hydrogen are fed into a reverse water-gas shift reactor to produce carbon monoxide and water that can be recycled to the electrolyser. The carbon monoxide and additional hydrogen are then sent to a

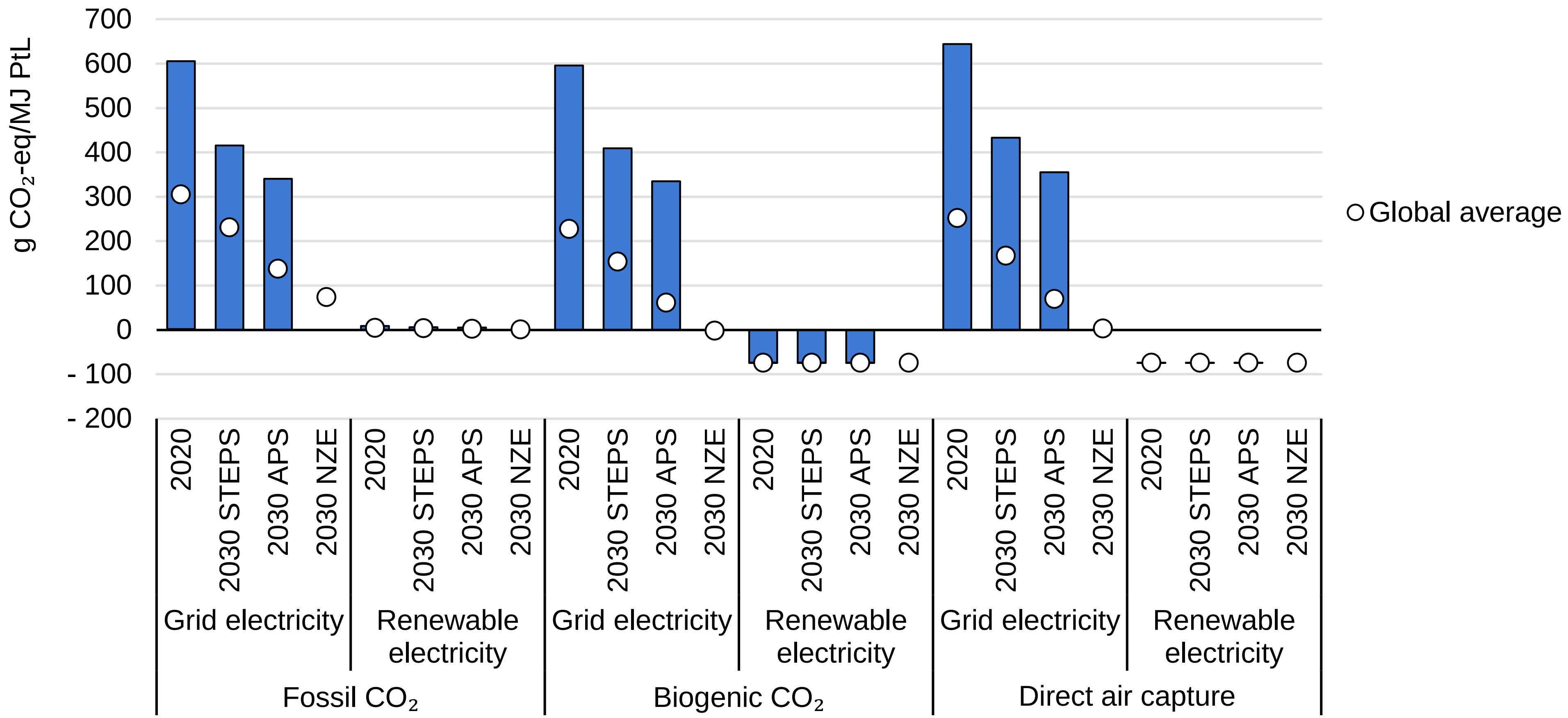
Fischer-Tropsch synthesis reactor to produce hydrocarbons in the diesel, kerosene and lighter fractions. Currently, the reverse water-gas shift reactor is one of the components at the lowest technological maturity, and therefore has the greatest opportunity for efficiency gains. Overall efficiency improvements could be made via improved heat integration across the power-to-liquids process as well as in the direct air capture plant when included. Additionally, oxygen produced from electrolysis can be used to heat the reverse water-gas shift in addition to off-gases from the Fischer-Tropsch reactor.

Variability and opportunities to reduce greenhouse gas emissions

Regional and temporal variation is influenced primarily by regional electricity emissions intensities. When renewable electricity is used to produce synthetic fuel, there is little regional variation since the energy consumption and emissions associated with delivery and dispensing are low. The synthetic fuel pathways using fossil-based CO_2 have higher well-to-tank emissions than the biogenic CO_2 or direct air capture pathways, because these pathways are not considered carbon-negative.

Well-to-tank emissions of synthetic fuel (power-to-liquids) pathways

Well-to-tank carbon intensity of synthetic fuel production by technology pathway, 2020 and 2030



Notes: PtL = power-to-liquids. Only global average is shown for the Net Zero Emissions by 2050 Scenario.
Sources: IEA Energy Data Centre, IEA Energy Technology Perspectives Supply model.

Chapter 4. Comparing lifetime well-to-wheel greenhouse gas emissions across new light-duty vehicles

Extending the scope of emissions analysis to a well-to-wheel basis

Well-to-wheel in the context of life-cycle assessment

To estimate the greenhouse gas emissions impacts of vehicles with different fuels and powertrains, there is a need to look beyond their rated tailpipe CO_2 emissions. A coherent and complete comparison requires analysis of the greenhouse gas emissions across the entire life cycle. It includes "vehicle-cycle" emissions – those incurred in vehicle manufacturing (including all components) and end-of-life (including recycling) – and "fuel-cycle" or "well-to-wheel" emissions, incurred in supplying fuel and operating the vehicle.

Previous IEA publications, including the Global EV Outlook 2019, and The Role of Critical Minerals in Clean Energy Transitions, compared the greenhouse gas emissions incurred by different light-duty vehicle powertrains on a full life-cycle basis. While a full life-cycle approach is needed to evaluate and compare the impacts of vehicle production and end-of-life across powertrains, Chapters 3 and 4 of this report focus on integrating and modelling the well-to-wheel greenhouse gas emissions into the IEA Mobility Model, a long-term transport modelling tool.[1]

Well-to-wheel in the context of long-term modelling

Well-to-wheel greenhouse gas emissions are analysed here within the context of wider energy systems modelling at the IEA. The aim of the assessment is not to compare all possible fuels, powertrains and feedstocks to identify the most favourable combinations. Instead, the scope is limited to fuel-powertrain combinations that are expected to play an important role for global decarbonisation as outlined in recent IEA Scenario modelling reports, including Energy Technology Perspectives 2020, World Energy Outlook 2021 and Net Zero by 2050.

The fact that the well-to-wheel greenhouse gas emissions modelling is being applied to IEA long-term scenario modelling outputs has implications for two fuel types: synthetic fuels and biofuels (especially hydrotreated vegetable oil and high blends of low-carbon cellulosic ethanol). Given the very high cost of synthetic fuels, as well as the land and resources required to produce them, in a net zero pathway these fuels are expected to be reserved to sectors and applications for which low-carbon alternatives are non-existent or scarce, especially shipping and aviation. Direct electrification,

[1] Potential future work will build on this initial analysis to explore fuel supply pathways in greater detail, and may also incorporate analysis on vehicle-cycle emissions, thereby extending the analytical scope to the entire life cycle. For this future work, analysts in the IEA Secretariat aim to collaborate with experts in the Technology Collaboration Programmes assembled under the Transport Coordination Group, and researchers at Argonne National Laboratory in the United States working on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model (GREET).

and in some cases reliance on fuel cell electric powertrains, enables light-duty vehicles to be operated far more cheaply than if using synthetic fuels. Similarly, biofuels are likely to be limited to sectors where emissions are hard to abate, since the sustainable supply of biomass is limited (see Chapter 5 of Energy Technology Perspectives 2020).

Estimating greenhouse gas emissions on a well-to-wheel basis

Various analytical and methodological choices affect the results reported here, some of which come from extending the analysis to a well-to-wheel basis. Three of these issues are:

- the gap between rated and real-world performance
- well-to-wheel emissions performance over the vehicle lifetime
- well-to-wheel methodological choices.

The gap between rated and real-world performance.[2] Rated fuel consumption and tailpipe emissions do not reflect actual on-road performance. In this report, all specific fuel consumption values are converted from the national test cycles used for compliance to the Worldwide Harmonized Light-Duty Vehicle Test Cycle (WLTC), using the zero-intercept conversion regressions developed by the International Council on Clean Transportation in 2014. More recent studies indicate that the gap between this test cycle and real-world fuel economy and emissions is 14% across conventional internal combustion engine vehicles. The gap varies across powertrains; it is generally larger in plug-in hybrid electric vehicles and can be larger for battery electric vehicles in cold-weather operations.

Well-to-wheel emissions performance over the vehicle lifetime. The emissions intensity of fuel supply pathways is projected to continue to decline, but the well-to-wheel performance of different vehicle powertrains will improve at different rates. The result is that the well-to-wheel greenhouse gas emissions performance of zero-emissions vehicle powertrains will improve faster than that of internal combustion engine vehicles, and the emissions gap between internal combustion engine vehicles and zero-emissions vehicles will be wider than it would be considering emissions only over the year in which the vehicle is sold. For clarity about assumptions and ease of interpretation, this chapter opens with a section on the implications for well-to-wheel greenhouse gas emissions of fleet-level scrappage and the average annual decline in annual mileage.

Well-to-wheel methodological choices. Different studies and regulations adopt different assumptions, methodologies and data sources in estimating well-to-wheel emissions. A key debate on methodological choices is whether to use allocational or

[2] For more discussion of this gap, see Chapter 4 of GFEI Working Paper 19.

consequential methods and, in the case of biofuels, the treatment of direct and indirect land-use change. Other methodological issues arise when considering impacts of and interactions between energy systems and agriculture, land use, and forestry; the duration of CO_2 emissions and sequestration; and crediting of emissions (and emissions reductions) and of co-products produced in energy and fuel conversions. In this study, we take an allocational approach, considering average emissions incurred in a given year as appropriate to report in a long-term energy systems modelling context. We consider emissions incurred in the cultivation and processing of biofuels feedstocks, and use allocational approaches as reported in the default methods of GREET. Further details on the data sources and methodological choices for the well-to-tank update are provided in Annex 2.

Integrating well-to-tank and tank-to-wheel emissions

Different vehicle powertrains have widely different characteristic efficiencies for converting the chemical energy stored as fuel in an internal combustion engine vehicle, in a battery in electric powertrains and in hydrogen in fuel cell vehicles to mechanical power to the wheels.

Typical tank-to-wheel efficiencies across powertrains

Powertrain	Representative
Gasoline internal combustion engine	22% (18-25%)
Diesel internal combustion engine	29% (25-32%)
Natural gas (CNG)	20% (16-22%)
Hybrid electric vehicle	36% (28-41%)
Plug-in hybrid electric vehicle	46% (35-75%)
Battery electric vehicle	75% (63-85%)
Fuel cell electric vehicle	55% (45-63%)

Notes: CNG = compressed natural gas. Estimated representative conversion efficiency from the energy stored in the fuel/battery to motive power at the wheels. Ranges consider new vehicles sold in 2019 in the medium car segment across advanced countries. In addition to technical parameters, real-world operations including average speeds and use of auxiliaries (e.g. air conditioning) lead to reductions in the values shown. In the case of plug-in hybrid electric vehicles, especially, the range varies widely depending on the share of electricity and gasoline fuelling the vehicle.

The different powertrain efficiencies mean that direct comparisons of the well-to-tank carbon intensity across fuels are misleading: 1 MJ of electricity carries a battery electric vehicle two to four times as far as a comparable gasoline internal combustion engine vehicle. Comparison of the emissions across powertrains requires integrating the well-to-tank and tank-to-wheel efficiencies and specific carbon emissions.

Because of the different conversion efficiencies and carbon intensities of well-to-tank fuel supply pathways (see Chapter 3), the share of well-to-tank emissions in the full well-to-wheel emissions varies characteristically across powertrains.

Representative shares of well-to-tank emissions in well-to-wheel emissions, 2019

Powertrain	Well-to-tank
Gasoline internal combustion engine vehicle	16%
Diesel internal combustion engine vehicle	14%
CNG vehicle	19%
Hybrid electric vehicle	16%
Plug-in hybrid vehicle	48-54%

Notes: Values based on global averages across the four highest-selling segments of light-duty vehicles sold in 2019. All emissions of battery electric vehicles and fuel cell electric vehicles are incurred in the well-to-tank stage. Shares for plug-in hybrid electric vehicles depend on the utility factor.

Comparing well-to-wheel greenhouse gas emissions performance across light-duty vehicles, 2019 and 2030

Well-to-wheel emissions over the vehicle lifetime

In general, light-duty vehicles are driven most intensively in the initial years after they are sold, and annual mileage declines thereafter until a car is scrapped. Vehicle lifetime and mileage decay patterns each depend on several factors, including owners' daily driving patterns (including whether several vehicles are owned by a household, or whether a vehicle is used to provide transport services, such as taxi or ride-hailing services) as well as fuel prices, geography, vehicle segment and other factors.

Surveys of average lifetimes and lifetime mileages across a wide range of countries provide evidence that vehicles are being driven more and scrapped later than at the turn of the century or even a decade ago.[1]

Typical light-duty vehicle lifetimes and lifetime mileages

Parameter	Average	Range
Lifetime	~21 years	~13-22 years
Lifetime mileage	~200 000 km	~150 000 – 210 000 km

The shape of mileage decay will also affect the lifetime average well-to-wheel greenhouse gas emissions (measured in grammes of CO_2 equivalent per kilometre).[2] The impact is most pronounced in zero-emission vehicles, since all operational emissions of battery electric vehicles and fuel cell electric vehicles come from supplying electricity and hydrogen, processes that show potential for rapid decarbonisation.[3]

Efficiency improvements and efforts to reduce emissions from oil and gas pathways can also curb the well-to-wheel emissions intensity of internal combustion engine vehicles. However, well-to-tank emissions account for only 14-19% of total well-to-wheel emissions in internal combustion engines and hybrid electric vehicles, and both the potential and the pace of carbon intensity reductions are slower than for electricity and hydrogen.

Fleet-level mileage decay curves can be drawn for three light-duty vehicles, each of which takes into account scrappage as well as mileage decay. On average, vehicles in the fleet are driven for 21 years and 200 000 km before being scrapped. In the case of

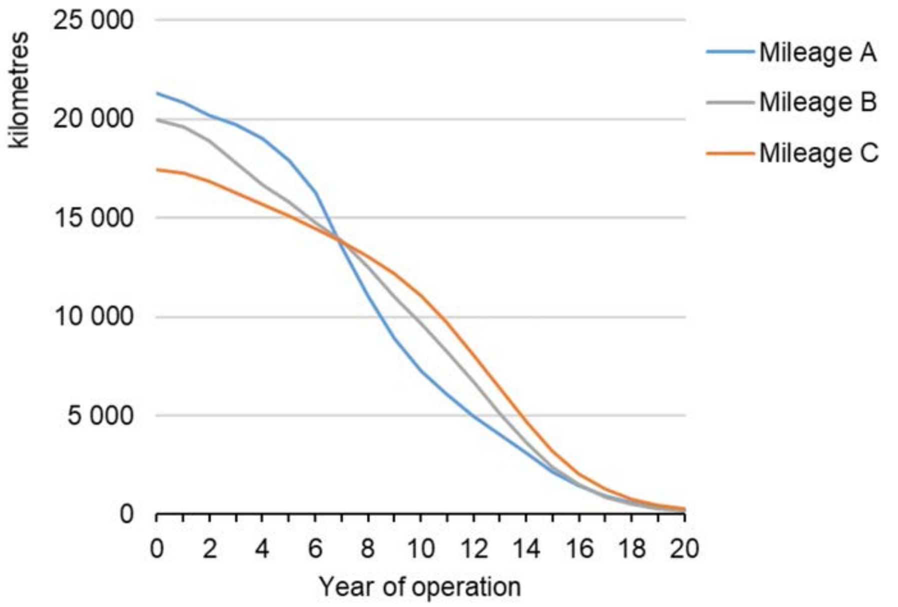
[1] For instance, recent studies of vehicle usage and survival include ones covering the People's Republic of China (hereafter, "China"), New Zealand, the United Kingdom and the United States. Recent studies investigating vehicle lifetime mileage include surveys from China, France, the United Kingdom and the United States. Recent studies investigating mileage attrition include studies performed in China, India and the United Kingdom. The IEA regularly compiles and compares these studies to assess representative usages, as well as drivers for differences in these parameters across countries and over time.

[2] As explained in further detail in Annex 2, calculations of tank-to-wheel emissions currently only include CO_2. Including other greenhouse gases (e.g. methane, nitrous oxide, black carbon) is a high-priority modelling improvement.

[3] Indeed, decarbonising the supply of these energy carriers, and especially electricity, is the foundation for decarbonising processes not only in transport, but for the energy system as a whole.

mileage profile A, the gap between the lifetime well-to-wheel emissions of a gasoline internal combustion engine vehicle and a battery electric vehicle is narrowest, as vehicles are driven the greatest share of their mileage when new. The opposite is the case for mileage case C; since a higher share of vehicle mileage is driven in the latter years, battery electric vehicles driving on lower-carbon-intensity electricity will emit less per kilometre on a well-to-wheel basis than in mileage case A, all else equal.

Illustrative fleet-level light-duty vehicle mileage decay over vehicle lifetime



The impact of alternative fleet-level vehicle lifetime emission trajectories can be illustrated by considering the weighted average passenger car sold in 2019 in the United States, and assuming a lifetime mileage of 200 000 km. For internal combustion engine vehicles, the annual total well-to-wheel emissions of curve A in the Stated Policies Scenario decline the least, as the well-to-tank carbon intensity reductions of the gasoline blend (including ethanol) provided to the vehicle are minor. For battery electric vehicles, mileage decay curve C results in a higher share of vehicle mileage in latter years, and in the Announced Pledges Scenario reductions in the carbon intensity of electricity generation result in the biggest decline in lifetime well-to-wheel emissions relative to the static case.

In the case of gasoline internal combustion engine vehicles, lifetime well-to-wheel emissions have a minor impact compared to the emissions incurred in the static case of the vehicle sold in 2019; gradual reductions in the well-to-tank carbon intensity of gasoline results in about 5% lower specific well-to-wheel emissions in the Stated Policies Scenario and 10% in the Announced Pledges Scenario.

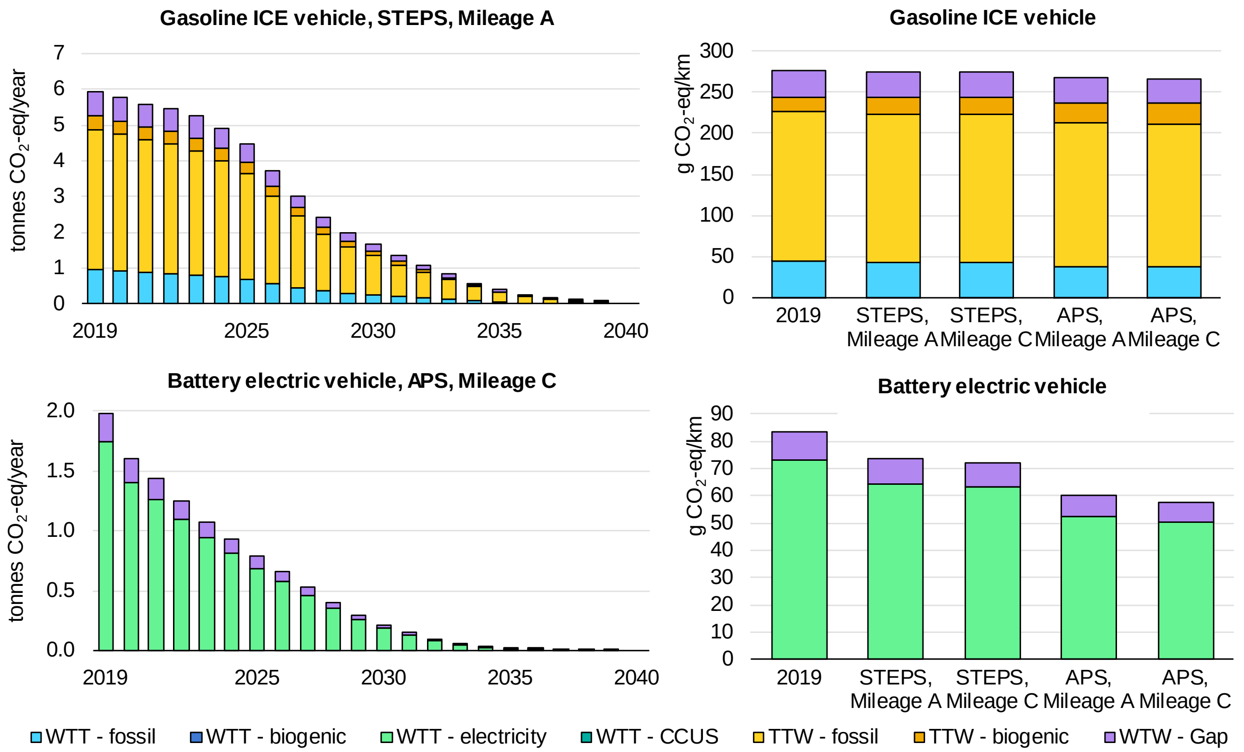
This finding contrasts starkly with the impact of considering lifetime well-to-wheel emissions for battery electric vehicles. Here, well-to-wheel emissions per kilometre over the vehicle lifetime are 12% to 31% lower than the specific emissions incurred in the first year of vehicle operations. The impact is greatest in the Announced

Pledges Scenario, where the carbon intensity of electricity declines faster, and in mileage case C, where the highest share of miles are driven in later years.

The comparisons of well-to-wheel emissions intensity in new vehicles in the rest of this chapter consider lifetime well-to-wheel emissions based on fleet average scrappage and the mileage decay B, and use the change in emissions intensity over lifetime mileage to consider potential improvement of performance over the vehicle lifetime.

Well-to-wheel greenhouse gas emissions intensity of battery electric vehicles over vehicle lifetime, compared with the first year of use

Illustrative annual well-to-wheel emissions of gasoline internal combustion engine vehicles and battery electric vehicles for the two extreme mileage decay cases, and specific well-to-wheel emissions in all four cases and in the first year of vehicle operation (static case)



Notes: ICE = internal combustion engine; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; WTT = well-to-tank; TTW = tank-to-wheel; WTW = well-to-wheel; CCUS = carbon capture, utilisation and storage. The results consider the weighted average fuel economy for a car sold in 2019 in the United States with a vehicle lifetime of 200 000 km. Mileage A and mileage C are based on the annual mileage distribution over the vehicle lifetime in “Illustrative fleet-level light-duty vehicle mileage decay over vehicle lifetime”. In the two figures on the right, the column labelled as 2019 refers to the static case in which mileage function is not taken into consideration.

Sources: IEA Mobility Model, September 2021 version; IEA analysis based on the IHS Markit database; ETP Supply Model; IEA Energy Data Centre.

Vehicle fuel economy performance and well-to-tank carbon intensity of supplying fuels determine well-to-wheel greenhouse gas emissions performance

Estimated well-to-wheel greenhouse gas emissions intensities[1] vary systematically within and across powertrains, vehicle segments and regions. Emissions performance varies most widely in conventional gasoline and diesel internal combustion engine vehicles, reflecting the range of models sold in different markets and across vehicle segments. The range in performance of CNG internal combustion engine vehicles is also wide, but less so, given the small sales volumes of this powertrain option.

Global average well-to-wheel emissions are highest in gasoline internal combustion engine vehicles, and are only slightly lower in diesel and CNG vehicles. In the Stated Policies Scenario, the average gasoline internal combustion engine light-duty vehicle sold in 2019 emits 212 g CO_2-eq/km, about 15% more than the average diesel or CNG internal combustion engine vehicle. The average conventional hybrid electric vehicle sold in 2019, meanwhile, emits 35% less than the average gasoline internal combustion engine vehicle (138 g CO_2-eq/km) in the same scenario. The global average emissions intensity decreases monotonically from the internal combustion engine powertrains to hybrid electric vehicles and fuel cell electric vehicles, and then to plug-in hybrids and battery electric vehicles.

Even across conventional internal combustion engine powertrains (including hybrid electric vehicles), there is a considerable degree of overlap in the estimated emissions performance, especially amongst light-duty vehicles sold in 2019 in the Stated Policies Scenario. The range in estimated rated well-to-wheel greenhouse gas emissions performance across vehicle segments (i.e. with city cars generally having the lowest well-to-wheel emissions and large SUVs the highest), is shown by the black bars in the Figures below for the 2019 Stated Policies Scenario alone.

Despite the clear rank order of the global average well-to-wheel emissions performance across powertrains, there are large degrees of overlap between internal combustion engine vehicles and hybrids, on the one hand, and between hybrids and zero-emission vehicle powertrains (fuel cell, plug-in hybrid and battery electric vehicles) on the other. The degree of overlap between non-hybrid internal combustion engine vehicles and zero-emissions vehicles is

[1] Emissions intensity of vehicle operations is reported in grammes of CO_2-eq per kilometre. All well-to-wheel greenhouse gas emissions are estimated based on 100-year global warming potential. See Annex 2.

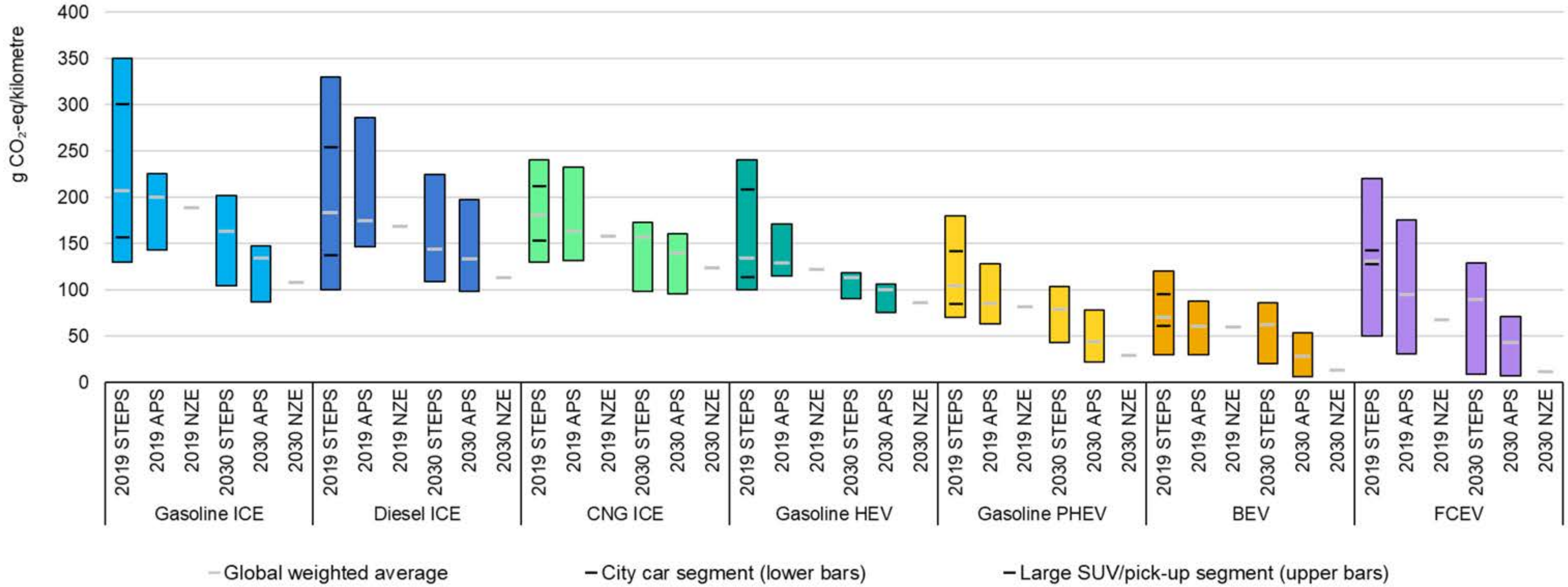
much smaller, particularly for vehicles expected to be sold in 2030 (in both the Stated Policies Scenario and Announced Pledges Scenario).

The Announced Pledges Scenario relies on shifting from internal combustion engine to zero-emission vehicles

In the Announced Pledges Scenario, well-to-wheel greenhouse gas emissions are reduced considerably by ensuring that large, heavy and more powerful internal combustion engine vehicles make up very small shares of global light-duty vehicle sales by 2030. Only zero-emissions vehicles sold in 2030 achieve global average well-to-wheel emissions of well below 100 g CO_2-eq/km, in both the Stated Policies Scenario and the Announced Pledges Scenario.

Average rated fuel economy performance and well-to-tank carbon intensity of supplying fuels determine well-to-wheel greenhouse gas emissions intensity

Well-to-wheel greenhouse gas emissions ranges across regions and countries in the Stated Policies Scenario and Announced Pledges Scenario



Notes: NZE = Net Zero Emissions by 2050 Scenario; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle. Grey bars show the global weighted average well-to-wheel greenhouse gas emissions performance. Coloured columns show the range of performance across all five regions covered in detail in this report (China, Europe, the United States, Japan, and emerging markets and developing economies). Black bars (2019 STEPS only) show the global weighted average performance of each powertrain in the city car segment (lower bars) and large SUV segment (upper bars), respectively (except for CNG ICE vehicles and FCEVs, where bars show minimum and maximum values across all segments sold).

Source: IEA Mobility Model, September 2021 version.

In 2019, battery electric vehicles had the lowest global average well-to-wheel greenhouse gas emissions – this is the case also in 2030 in IEA Scenarios

Well-to-wheel emissions of light-duty vehicles sold in 2019

In 2019, the well-to-wheel greenhouse gas emissions intensity of battery electric vehicles was the lowest across all powertrains and in each of the four highest-selling light-duty vehicle size segments.[1,2]

Battery electric vehicles in 2019 had an average well-to-wheel greenhouse gas emissions intensity up to 68% lower than gasoline internal combustion engine vehicles within the same size segment. The difference is largest in the large car and in the small SUV size segment. A growing number of electric small SUV models have become commercially available in recent years and the model offering will continue to grow rapidly in the next few years. Even in the city car segment, the per-kilometre well-to-wheel emissions intensity of battery electric vehicles is around two-thirds that of gasoline internal combustion engine vehicles.

Plug-in hybrids are estimated to be the second-lowest emitting powertrain.[3] Well-to-tank emissions (both in electricity and gasoline supply chains) accounted for approximately 50% of the total well-to-wheel emissions of plug-in hybrids.

Global average well-to-wheel greenhouse gas emissions of gasoline hybrid electric vehicles were the next lowest across all segments except small SUVs. They were 26-38% lower than those of gasoline internal combustion engine vehicles within the same size segment, showing the efficacy of hybridisation as a means to cut the emissions of internal combustion engine vehicles.

The well-to-wheel greenhouse gas emissions intensity of fuel cell electric vehicles sold in 2019 was 13% higher than that of hybrid electric vehicles in the medium car segment and slightly better than plug-in hybrids in the small SUV segment. Reducing the well-to-wheel emissions of fuel cell electric vehicles to bring them to similar performance as other zero-emissions vehicles will require lowering the well-to-tank carbon intensity of the pathways for supplying

[1] Values chosen for the parameters are weighted global averages. For fuel economy, the global average is weighted with regional light-duty vehicle sales in 2019. The global average tank-to-wheel and well-to-tank emission factors of the different fuels are weighted using the regional consumption of that fuel in 2020 and in 2030 for the Stated Policies Scenario and Announced Pledges Scenario.

[2] All of the emissions incurred by battery electric vehicle operations are incurred in the well-to-tank phase (electricity generation, transmission and distribution, and charging).

[3] This is based on the assumption that the global average utility factor in 2019 was 50%, except in regions where the weighted-average regulatory utility factor could be estimated based on top-selling plug-in hybrid models. The real-world greenhouse gas emissions performance of plug-in hybrids depends, however, on the share of annual mileage driven in electric mode, which varies considerably according to driving and charging patterns and plug-in hybrid model. For further discussion of these issues and their policy implications, see the forthcoming IEA article, "The role of plug-in hybrid electric vehicles in decarbonising road transport."

hydrogen to these vehicles. This can be achieved by switching to electrolysis that uses electricity generated from renewables or other low-carbon sources; by switching to biomethane steam reforming, gasification or another technology to produce hydrogen; and/or by equipping such technologies with CCUS.

Diesel vehicles had similar well-to-wheel greenhouse gas emissions intensity as hybrid electric vehicles in the city car segment, even though only 5% of city cars sold were diesels. Gasoline, Diesel, and CNG internal combustion engine vehicles had the highest well-to-wheel greenhouse gas emissions per kilometre across all segments.

Projected well-to-wheel greenhouse gas emissions of light-duty vehicles sold globally in 2030

Differences in the Stated Policies Scenario and Announced Pledges Scenario trajectories of well-to-wheel greenhouse gas emissions intensities reflect the policies that would be needed to enable countries and regions with net zero pledges to achieve their stated goals. Such policies need to accelerate market diffusion of technologies in fuel supply chains (well-to-tank) and vehicle powertrains (tank-to-wheel). The level of policy ambition needed to achieve well-to-wheel emissions reductions in the Net Zero Emissions by 2050 Scenario exceeds even the Announced Pledges Scenario, and hinges in particular on rapid adoption of zero-emission vehicles.

Policies that can reduce the carbon intensity of fuel supply chains include fiscal and regulatory measures that encourage the adoption of low-carbon fuels, such as low-carbon fuel standards.[4] Policies that promote the adoption of renewables and other low-carbon electricity generation and hydrogen production technologies are also critical, given the more rapid shift in the Announced Pledges Scenario to zero-emission vehicles.

On the vehicle side (tank-to-wheel), more stringent fuel economy and/or CO_2 emissions standards, zero-emissions vehicle sales requirements, and even internal combustion engine phase-outs will be needed to achieve many of the most ambitious net zero pledges.

Between 2019 and 2030, well-to-wheel greenhouse gas emissions intensity is projected to fall across all powertrains, albeit at different rates. These rates depend on policies that can reduce the carbon intensity of fuel supply chains (well-to-tank) and fuel economy and/or CO_2 emissions standards that mandate vehicle efficiency improvements. These result in differences in the improvements in powertrains in different countries and regions, and between the Stated Policies Scenario and the Announced Pledges Scenario.

[4] California adopted a low-carbon fuel standard in 2013. Similar policies that use carbon intensity as a performance metric for alternative transport fuels and energy carriers have subsequently been adopted in Canada (Clean Fuel Standard), Europe (latest revisions under Fit for 55 of the Renewable Energy Directive III), and Brazil (RenovaBio), among others.

Despite differing regional trends, in nearly all countries and segments, and across both scenarios, battery electric vehicles remain the lowest-emitting powertrain, and have the greatest potential for well-to-wheel emissions reductions overall by 2030. The pace of reduction is primarily a function of the reduction in the carbon intensity of electricity generation.

Global average well-to-wheel emissions intensities, in the Announced Pledges Scenario and Stated Policies Scenario, 2019 and 2030

Powertrain	WTW GHG emissions intensity (gCO_2-eq/km)			
	2019 STEPS	2019 APS	2030 STEPS	2030 APS
Gasoline ICE	205	200	160	130
Diesel ICE	180	170	140	130
CNG ICE	180	160	160	140
HEV	135	130	110	100
PHEV	105	90	80	40
BEV	70	60	60	30
FCEV	130	95	90	40

Notes: WTW = well-to-wheel. Ranges are based on the Worldwide Harmonized Light-Duty Vehicle Test Cycle rated performance. Well-to-wheel carbon intensity across all passenger light-duty vehicles, values rounded for simplicity. Carbon intensity values for FCEVs in the Announced Pledges Scenario and Stated Policies Scenario reported here are a range between values using electrolytic hydrogen and natural gas steam methane reforming pathways. Carbon intensity values for ICE vehicles, HEVs and PHEVs include biofuel blending.

Deep emissions reductions can also be achieved in fuel cell electric vehicles, depending on the carbon intensity of hydrogen production, and in plug-in hybrids, according to the share of kilometres driven on electricity.

When compared with zero-emission vehicles, well-to-wheel greenhouse gas emissions reductions in hybrid electric vehicles are limited, reflecting narrow prospects for further efficiency gains.

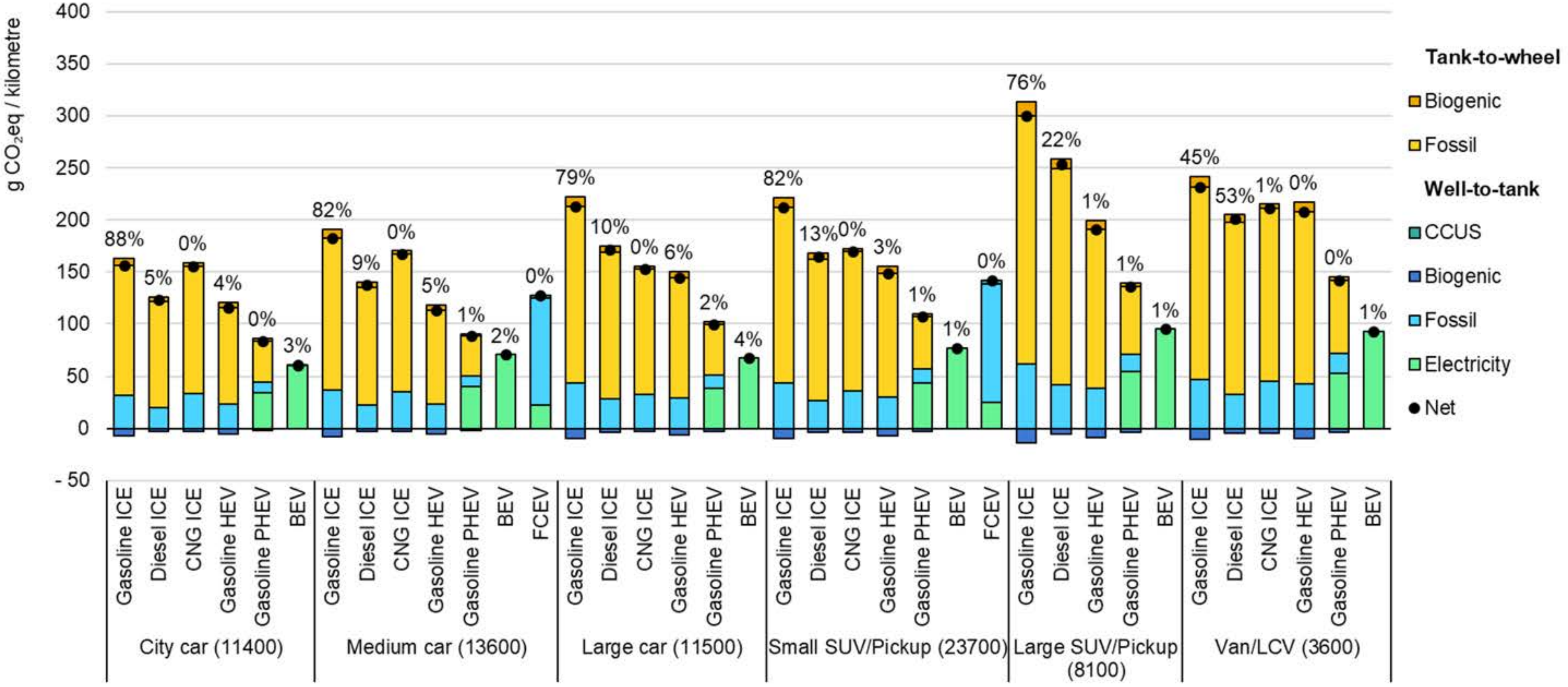
Powertrains based solely on an internal combustion engine (gasoline and diesel)[5] have greater potential for improvements in their conversion efficiency than zero-emission vehicles and hybrid electric vehicles, given the fact that conversion efficiencies of fuel cell, plug-in hybrid and battery electric vehicles are already high. However, the pace and potential for reductions in the energy carriers that supply zero-emission vehicles far exceeds that of liquid and gaseous fuels (regardless of whether they are of fossil or biogenic origin), because renewables and nuclear power, as well as fossil production equipped with CCUS, have the potential to produce very low-carbon electricity and hydrogen.

Despite the improvements in vehicle efficiency achieved in internal combustion engine vehicles by 2030, their overall emissions performance continues to lag behind that of zero-emission vehicles.

[5] The potential for further improvements in CNG vehicles is more limited, given limited future investments in CNG engine efficiency and structural shifts to larger vehicles. Instead, well-to-wheel greenhouse gas emissions reductions in CNG vehicles are projected to come about mostly through blending of biomethane.

Battery electric vehicles have the lowest well-to-wheel emissions in all segments

Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019

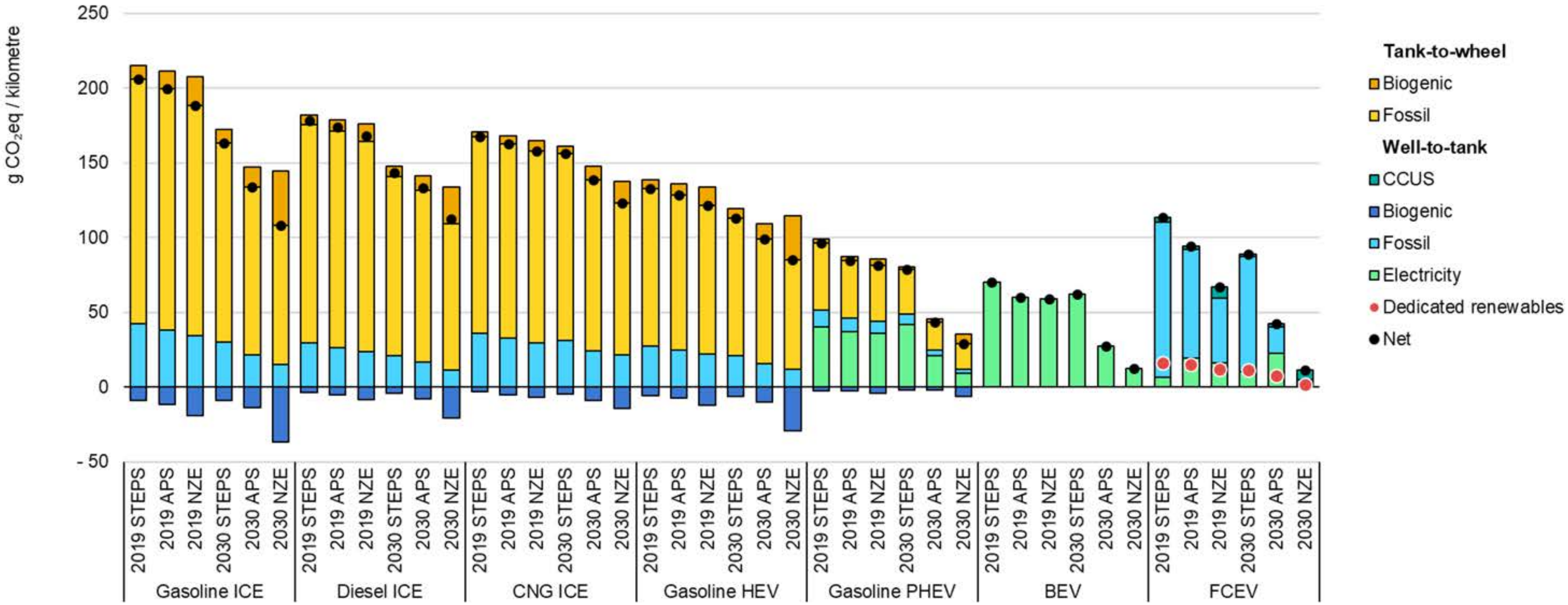


Notes: LCV = light commercial vehicle. The total sales by segment is given in parentheses (in thousand vehicles) next to the size segment label. The percentage above each powertrain indicates its sale share within that segment in 2019. The black dots indicate the net well-to-wheel greenhouse gas emissions, considering the negative component from biogenic emissions. Fossil and biogenic emissions are those generated in supplying (well-to-tank) or combusting (tank-to-wheel) fossil fuels and biofuels. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 globally. CCUS indicates the emissions incurred in producing hydrogen and biofuels in plants equipped with CCUS.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

Battery electric vehicles will continue to emit the least in 2030

Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, 2019 and 2030 (projected)



Notes: For FCEVs, the red dots show the well-to-wheel emissions incurred if hydrogen were to be produced via electrolysis with dedicated renewable sources. The height of the stacked column shows instead total well-to-wheel greenhouse gas emissions of FCEVs considering the current and projected share of hydrogen production pathways. Therefore, the difference between the red column and the total indicates the theoretical well-to-wheel greenhouse gas emissions reduction potential of FCEVs. The carbon intensity of global electricity generation improves 26% between 2019 and 2030 in the Stated Policies Scenario and a further 30% in 2030 between the Announced Pledges Scenario and the Stated Policies Scenario. The utility factor of PHEVs is assumed to improve by six percentage points between 2019 and 2030 in the Stated Policies Scenario and by a further nine percentage points in 2030 between the Stated Policies Scenario and the Announced Pledges Scenario. The 2019 and 2030 emissions show the lifetime emissions for a vehicle sold in 2019 and 2030, respectively, in each scenario, according to the evolution of the well-to-tank carbon intensity.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

China: Ambitious policies need to curb SUVs while boosting zero-emission vehicles

Well-to-wheel greenhouse gas emissions of light-duty vehicles sold in China in 2019

Sales of SUVs have been increasing in China over the past decade, faster than in any other major vehicle market, undermining progress in fuel economy. Most diesel cars sold in China were large SUVs; overall, gasoline internal combustion engine cars had the highest well-to-wheel greenhouse gas emissions intensity across the whole car fleet.[1]

Battery electric vehicles produced the least emissions in China in 2019 within each size segment, despite a relatively high carbon intensity of grid electricity (around 670 g CO_2-eq/kWh for final electricity) compared with the global average (500 g CO_2-eq/kWh). The battery electric vehicle sales mix was dominated through 2019 by cars in the small, medium and large segments (totalling around 500 000 sales), but 165 000 small SUV battery electric vehicles were sold as well, and the market for larger and luxury battery electric vehicles has continued to grow.

China has focused on deploying fuel cell electric vehicles in heavier segments (buses and light commercial vehicles), which explains why in 2019 there were no sales of passenger car fuel cell electric vehicles.[2]

Projected well-to-wheel greenhouse gas emissions of light-duty vehicles in China in 2030

In the Stated Policies Scenario, fuel economy policy drives a 34% reduction in the well-to-wheel greenhouse gas emissions of gasoline internal combustion engines sold in China between 2019 and 2030. This is slightly less than the fuel economy improvements mandated under the “dual credit” policy, reflecting the limited potential for reductions in the well-to-tank carbon intensity of gasoline. There is little blending of biofuels, with the blending share of ethanol increasing from 2% to around 3% in 2030 under the Stated Policies Scenario, with little impact on well-to-wheel emissions.

Emissions decline further as shares of low- and zero-emission vehicles grow to nearly 40% of total sales by 2030, in line with

[1] Well-to-wheel greenhouse gas emissions of diesel internal combustion engine vehicles were higher than those of gasoline internal combustion engine cars in the city and medium segments because only a few models, which tended to be much heavier than their gasoline counterparts, were sold in those segments.

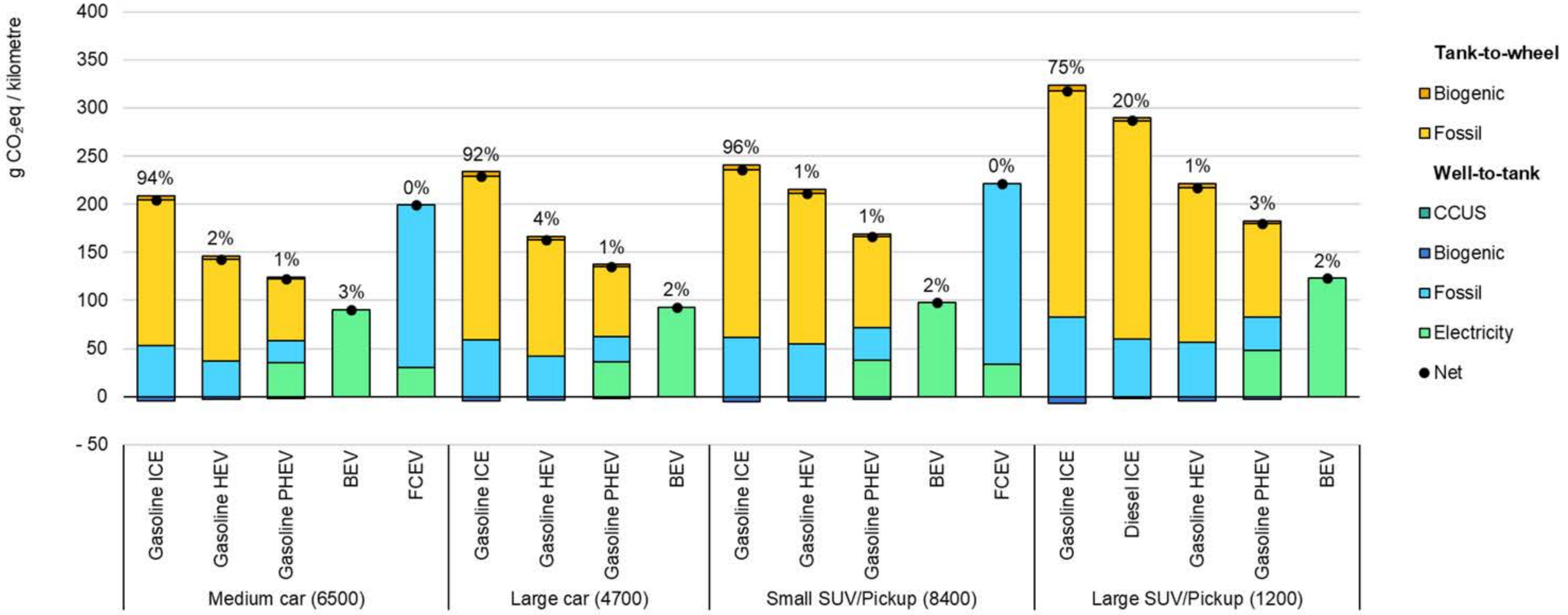
[2] The well-to-tank factor associated with hydrogen production in China is higher than for most other regions, as around 15% is produced by coal gasification, a more carbon-intensive process than the more commonly used natural gas steam methane reforming. This neglects the fact that much of the hydrogen supplied to commercial vehicle fleets in China is produced as a by-product of industrial processes.

policy targets. The well-to-wheel greenhouse gas emissions intensity reductions in hybrid electric vehicles (27%) and plug-in hybrids (23%) are less marked than for gasoline internal combustion engines, reflecting the more limited potential for improvements from the already lower baseline in these vehicles.

Driven by rapid reductions in the well-to-tank carbon intensity of the grid mix, the well-to-wheel emissions intensity of battery electric vehicles declines by 41% from 2019 to 2030 in the Announced Pledges Scenario. LNG tanker. Taking into account the energy needed both to liquefy natural gas and to turn LNG back into gas, around 11% of the gas originally arriving at the liquefaction terminal is consumed.

Battery electric cars sold in China provided well-to-wheel greenhouse gas reductions of 55-60% relative to gasoline internal combustion engine cars in 2019

Rated well-to-wheel emissions of new light-duty vehicle sales in China, by size segment, 2019

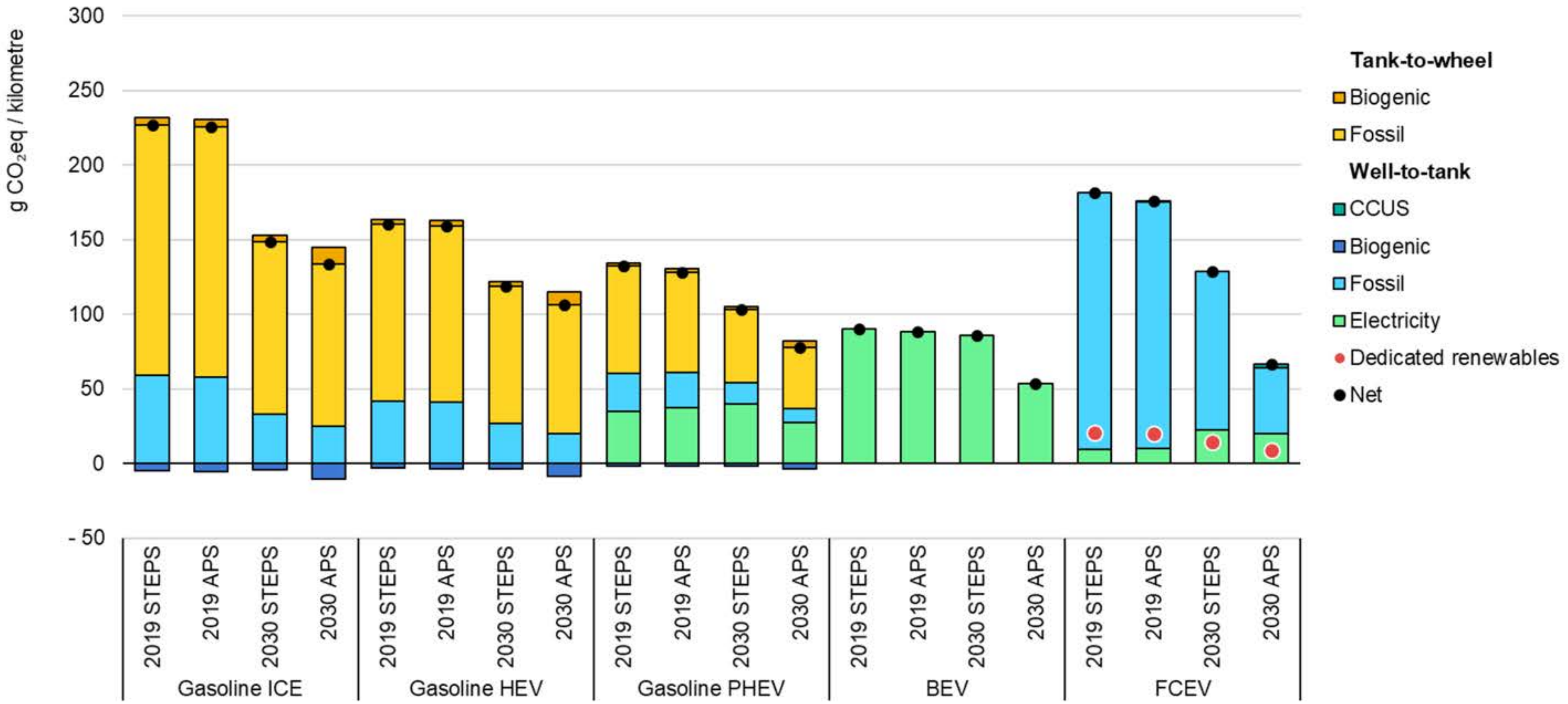


Notes: The figure shows the top four light-duty vehicle segments, accounting for 90% of light-duty vehicle sales in China in 2019. An explanation of legends and acronyms is provided in the notes for Figure *Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019*. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 in China.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

China's "dual credit" system is set to deliver some emissions benefits, but substantial reductions can be achieved by boosting electric vehicle sales shares and decarbonising electricity

Rated well-to-wheel emissions of new light-duty vehicle sales in China, 2019 and 2030



Notes: An explanation of legends and acronyms is provided in the notes for Figure Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019. The figure shows the Announced Pledges Scenario projection for China, which differs from the Stated Policies Scenario only beyond 2030, as the near-term trajectory has been set under China's 14th Five-Year Plan.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

In the United States, the Announced Pledges Scenario shows the potential of proposed new standards, and low-carbon electricity and hydrogen

Well-to-wheel emissions of light-duty vehicles sold in the United States in 2019

As in all regions, well-to-wheel greenhouse gas emissions of battery electric vehicles were the lowest across all powertrains and segments in 2019 in the United States, with specific emissions 55% to 71% lower than those of gasoline internal combustion engine vehicles across the four highest-selling segments.

Fuel cell electric vehicles performed slightly worse than battery electric vehicles. The well-to-tank emissions intensity of producing hydrogen by natural gas steam methane reforming (which in the United States accounts for about 90% of production) is similar to the well-to-tank emissions intensity of providing electricity to vehicles in the United States. So the gap in emissions between the two powertrains is mostly due to their relative conversion efficiency: 75% for battery electric vehicles versus 55% for fuel cell electric vehicles.

Well-to-wheel greenhouse gas emissions of gasoline internal combustion engine vehicles were highest across all size segments, ranging from 160 g CO_2-eq/km to 280 g CO_2-eq/km. These emissions are higher than in other regions because light-duty vehicles sold in the United States are larger and heavier (see Chapter 2). Hybrid electric vehicles have well-to-wheel emissions 32% to 45% lower than gasoline internal combustion engine vehicles, with a slight variation in this reduction across segments.

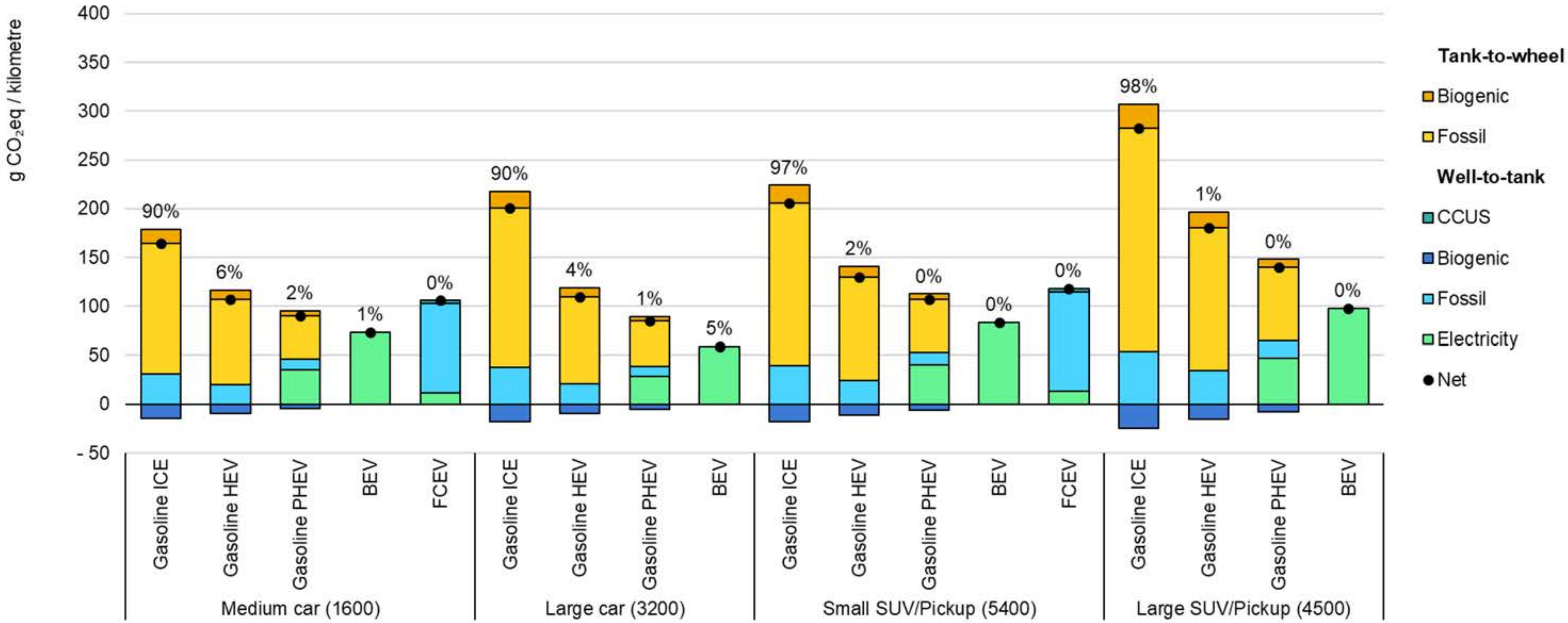
Projected well-to-wheel emissions of light-duty vehicles sold in the United States in 2030

The well-to-wheel greenhouse gas emissions of gasoline internal combustion engine cars and trucks decline by less than 10% between 2019 and 2030 under the Stated Policies Scenario (which considers only the current Safer Affordable Fuel-Efficient [SAFE] rule), whereas they decline by almost 50% in the Announced Pledges Scenario, which is aligned with the proposed new corporate average fuel economy standards (see Chapter 1). Emissions reductions are mostly achieved through fuel economy improvements. Blending of biofuels with gasoline and diesel increases in the Announced Pledges Scenario, reaching 17% for ethanol and 4% for biodiesel in 2030. These blending rates have little impact on the overall well-to-wheel emissions of internal combustion engine and hybrid vehicles.

Battery electric vehicles continue to be the least-emitting powertrain in the United States in both scenarios analysed. The pace of the shift to lower-carbon electricity generation in the United States is the main factor spurring this improvement: the weighted average well-to-wheel emissions across size segments decline from around 62 g CO_2-eq/km in 2019 to around 50 g CO_2-eq/km in 2030 in the Stated Policies Scenario and to almost 10 g CO_2-eq/km under the Announced Pledges Scenario. Fuel cell electric vehicles in 2030 in the Announced Pledges Scenario manage to achieve well-to-wheel emissions reductions similar to those of battery electric vehicles, thanks to equipping steam methane reforming with CCUS and switching hydrogen production to electrolysis using electricity from dedicated renewables.

In the United States, zero-emission vehicles already achieve substantial emissions reductions

Rated well-to-wheel emissions of new light-duty vehicle sales in the United States, by size segment, 2019

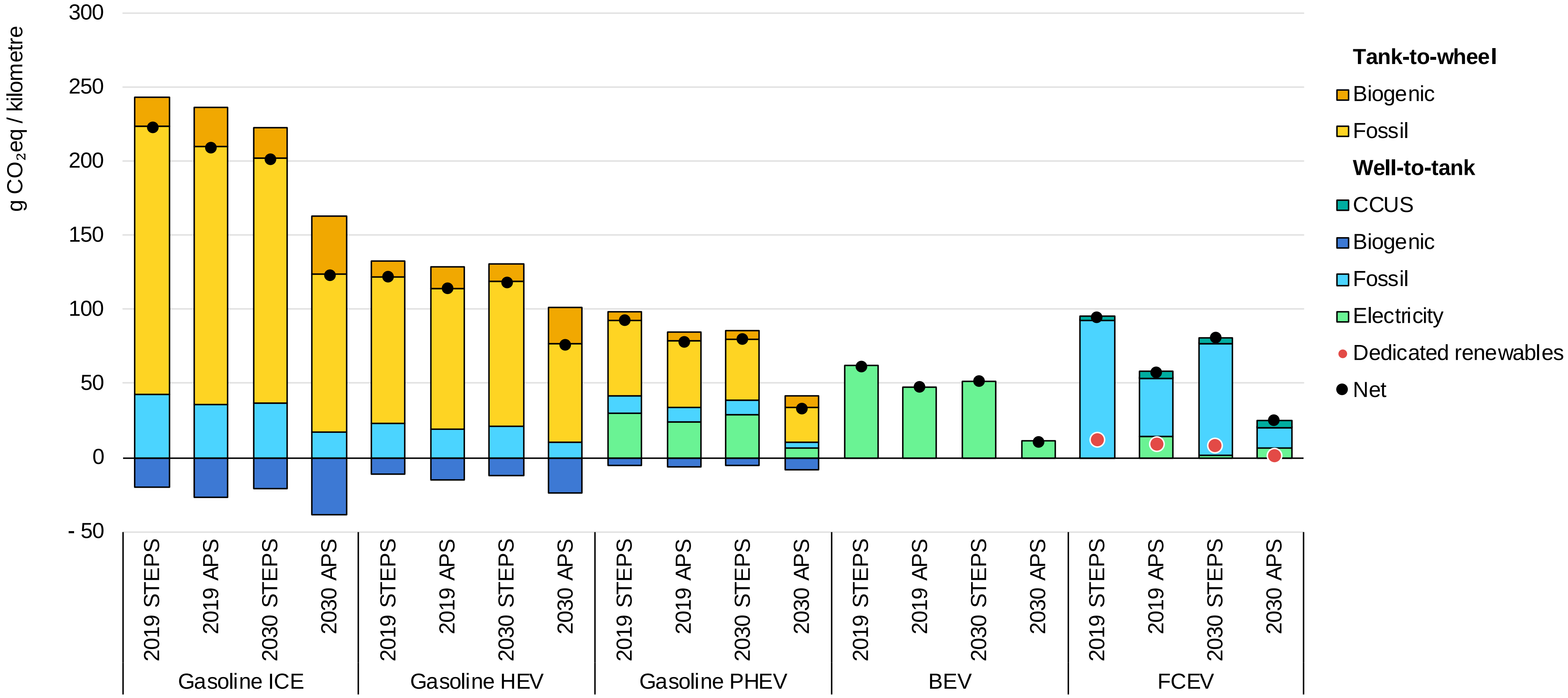


Notes: The figure shows the top four light-duty vehicle segments, accounting for 97% of light-duty vehicle sales in the United States in 2019. An explanation of legends and acronyms is provided in the notes for *Figure Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019*. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 in the United States.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

The United States can reduce emissions by implementing the proposed new fuel economy standards

Rated well-to-wheel emissions of new light-duty vehicle sales in the Unites States, 2019 and 2030



Notes: Explanation of legends and acronyms is provided in the notes for Figure Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019.
Source: IEA Mobility Model (2021 September version).

Both internal combustion engines and EVs sold in the European car market perform well, but ensuring that light-duty vehicles contribute to Europe's pledges for carbon neutrality requires further action

Well-to-wheel emissions of light-duty vehicles sold in Europe in 2019

The well-to-wheel greenhouse gas emissions of battery electric vehicles sold in the European market were the lowest amongst all regions covered in this summary – about 35 g CO_2-eq/km.[1] This is largely due to the low carbon intensity of final electricity used to charge electric vehicles in Europe (about 330 g CO_2-eq/kWh).

The well-to-wheel emissions of light-duty internal combustion engine vehicles sold in Europe were also lower than world averages (by 16% for gasoline, 15% for diesel and 12% for CNG vehicles). These reductions reflect the progress achieved by Europe's CO_2 emissions standards, though these standards stalled in 2018-2019 (see Chapter 1). Most CNG ICE cars are sold in the city and medium car segments in Italy, where they accounted in 2019 for 3% and 5% of sales in those segments, respectively.

Well-to-wheel greenhouse gas emissions of fuel cell electric vehicles sold in 2019 were intermediate between battery electric vehicles and plug-in hybrids, reflecting the lower well-to-wheel energy efficiency of fuel cell electric vehicles relative to battery electric vehicles.

Projected well-to-wheel emissions of light-duty vehicles sold in Europe in 2030

Aggressive promotion of renewables and low-carbon electricity generation reduces the well-to-wheel greenhouse gas emissions intensity of battery electric vehicles by 43% by 2030 in the Stated Policies Scenario, to reach 20 g CO_2-eq/km, and by 70% in the Announced Pledges Scenario relative to the Stated Policies Scenario in 2030, to reach 6 g CO_2-eq/km. Fuel cell electric vehicles show their potential by 2030 in the Announced Pledges Scenario to achieve well-to-wheel emissions on par with other zero-emissions vehicles, assuming that hydrogen can be generated from natural gas steam methane reforming equipped with CCUS or produced by electrolysis using very low-carbon electricity.

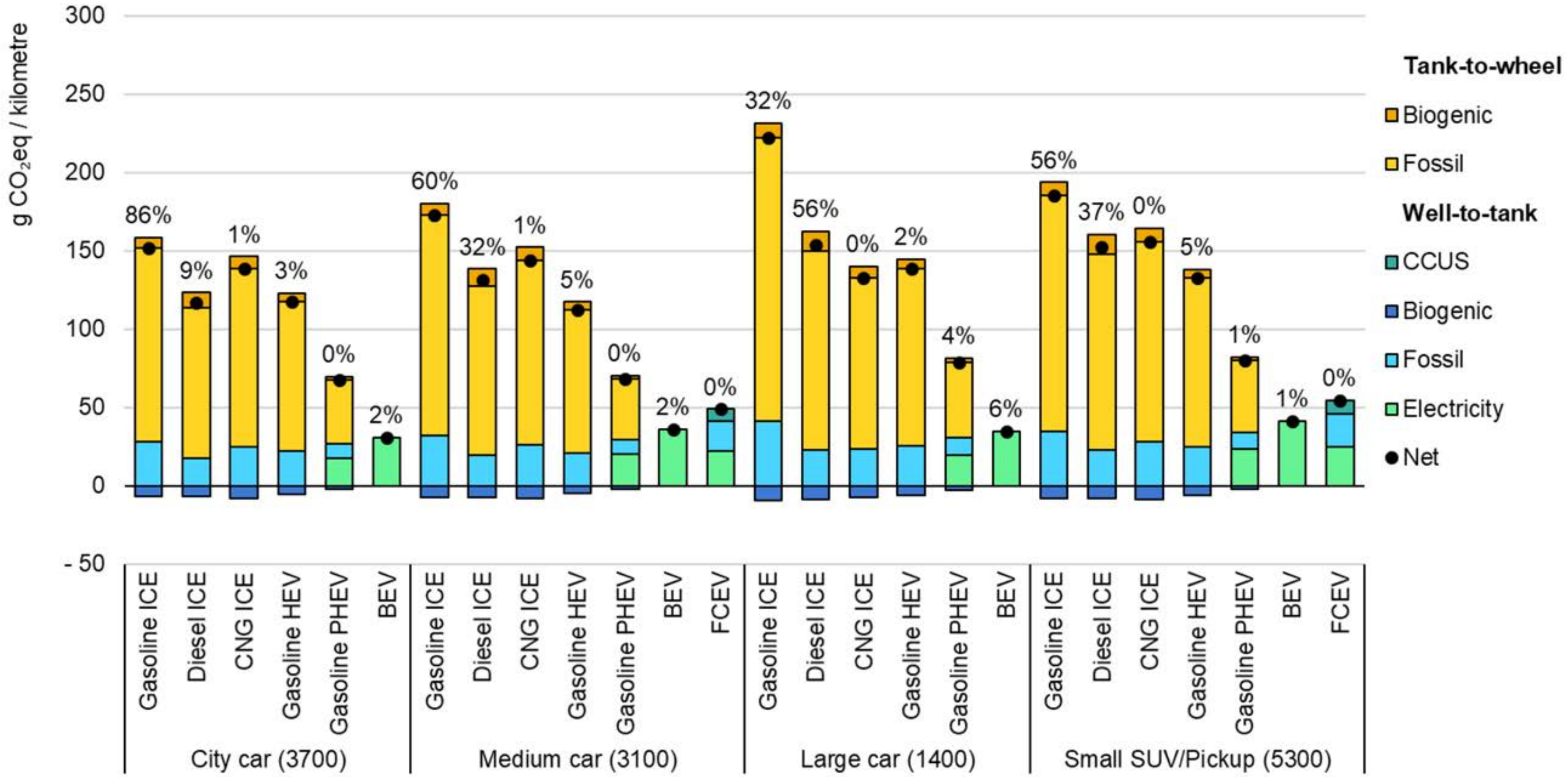
The well-to-wheel emissions intensity of all internal combustion engine vehicles in the Stated Policies Scenario declines at rates determined primarily by Europe's revised CO_2 standards: by 40% in

[1] Electric vehicles sold in Scandinavian countries such as Sweden and Norway also benefit from low-carbon-intensity electricity generation.

gasoline and 28% in diesel vehicles. Well-to-wheel emissions reductions lag behind CO2 standards, given slower reduction in the well-to-tank emissions of liquid fuels. Proposed revisions to the Renewable Energy Directive II policy under the European Union's Fit for 55 package contribute small reductions in well-to-tank emissions intensity by providing incentives for production of low-carbon ethanol and biodiesel.

CO_2 emissions standards and low-carbon electricity enable Europe to exceed global average well-to-wheel emissions reductions

Rated well-to-wheel emissions of new light-duty vehicle sales in Europe, by size segment, 2019

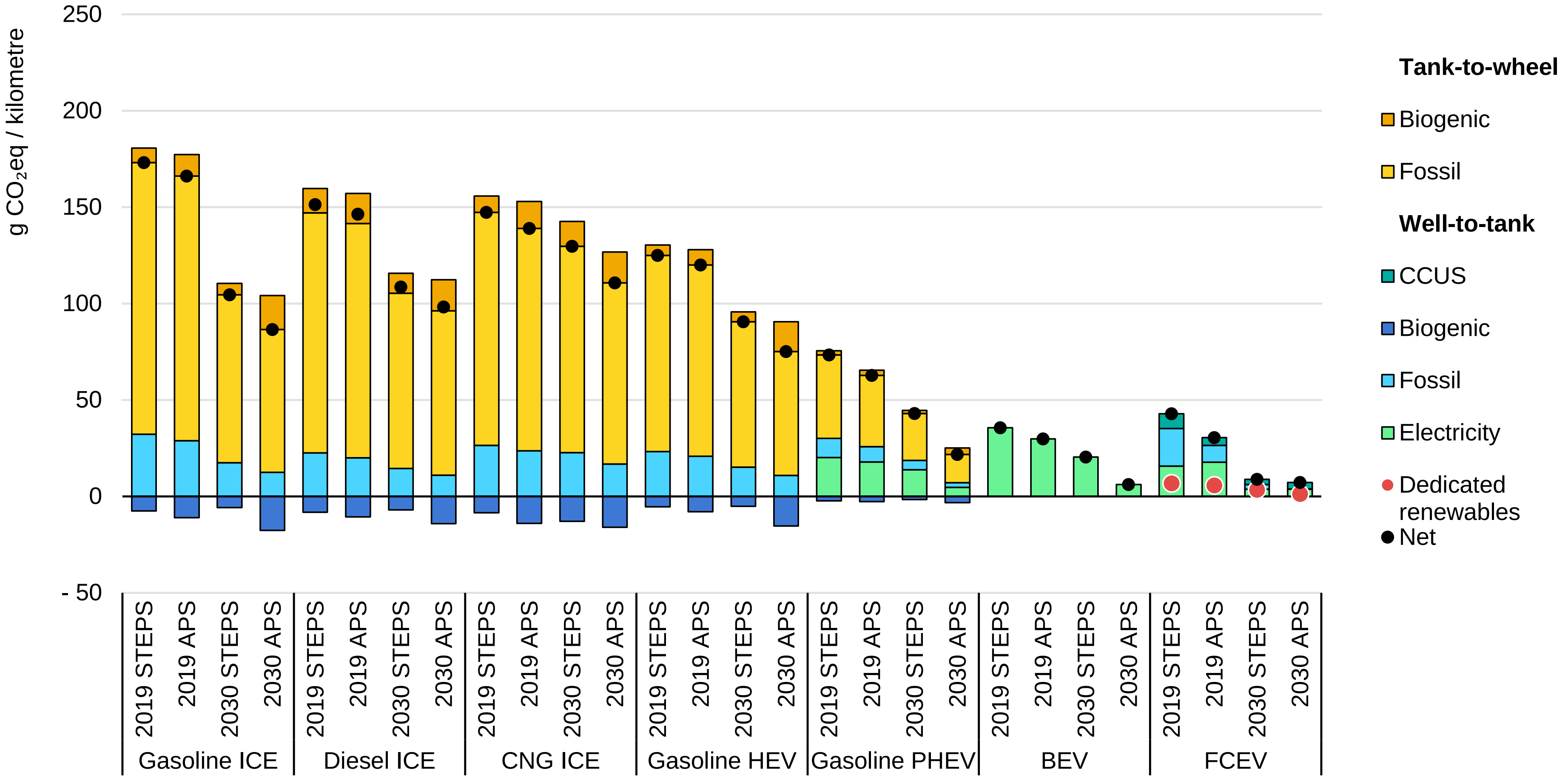


Notes: The figure shows the top four light-duty vehicle segments, accounting for 88% of light-duty vehicle sales in the European Union, in 2019. An explanation of legends and acronyms is provided in the notes for the Figure *Rated well-to-wheel emissions of new light-duty vehicle sales worldwide*, by size segment, 2019. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 in Europe.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

Europe's revised CO_2 emissions standards and energy policies could ensure that light-duty vehicles contribute substantially to its carbon neutrality goal

Rated well-to-wheel emissions of new light-duty vehicle sales in Europe, 2019 and 2030



Notes: Explanation of legends and acronyms is provided in the notes for *Figure Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019.*
Source: IEA Mobility Model (2021 September version).

Japan's new light-duty vehicles sold in 2019 had among the lowest well-to-wheel emissions across major car markets

Well-to-wheel emissions of light-duty vehicles sold in Japan in 2019

Over half of new light-duty vehicles sold in Japan were in the city car segment, a share unrivalled in any other developed country. With a weighted average well-to-wheel emissions intensity of around 150 g CO_2-eq/km, the emissions performance of gasoline internal combustion engine vehicles sold in Japan was 26% lower than the global average in 2019.

Emissions of hybrid electric vehicles were also slightly below the global average. Given the fact that these two powertrains were the most sold across all the four main size segments, and that Japan had the world's highest share of hybrid electric vehicle sales, the well-to-wheel greenhouse gas emissions of new light-duty vehicles sold in Japan was among the lowest in developed countries.[1]

In Japan in 2019, battery electric vehicles were the best performing powertrain in terms of well-to-wheel emissions, with specific emissions of 70 g CO_2-eq/km to 120 g CO_2-eq/km.

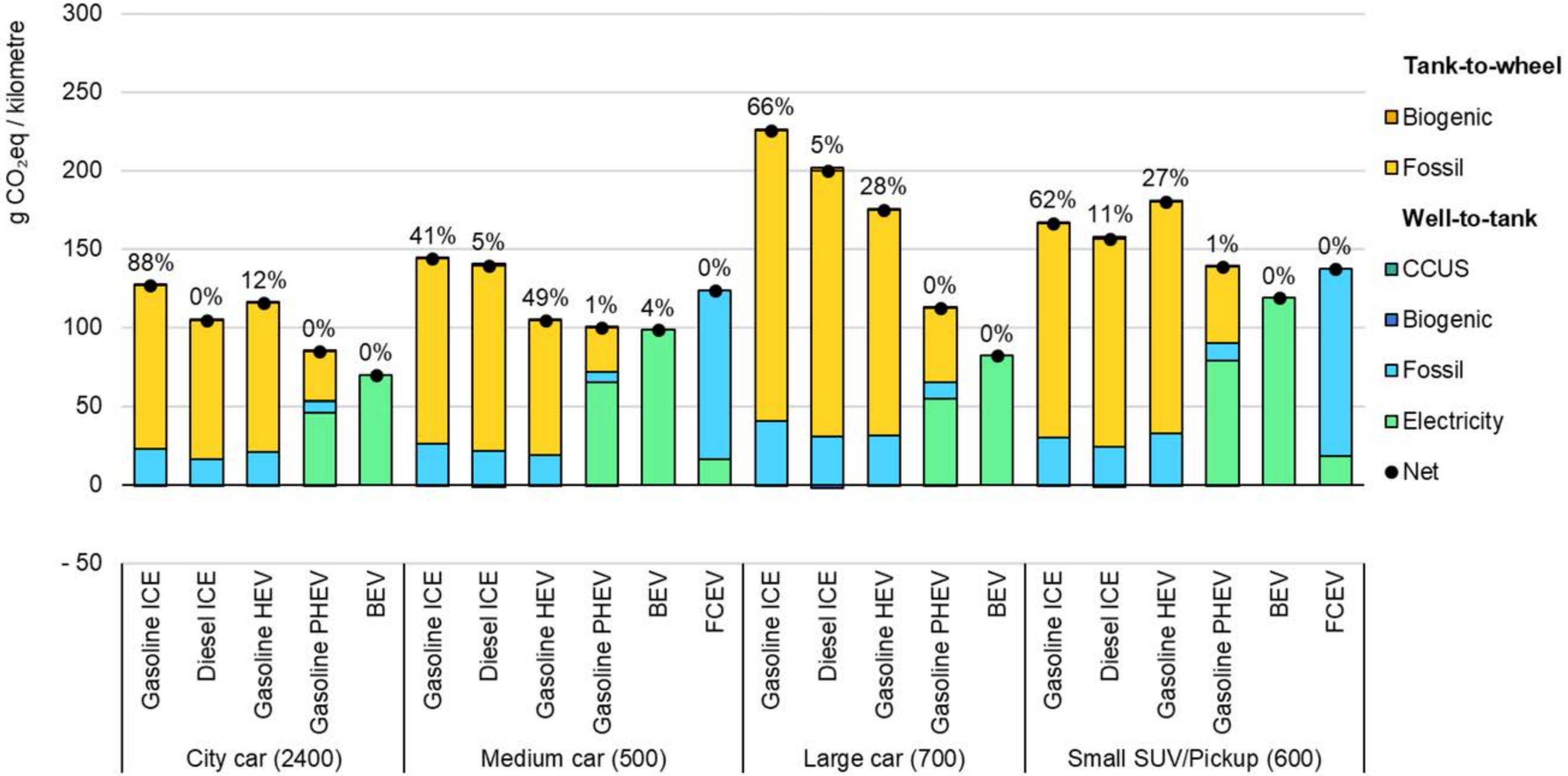
Plug-in hybrids had the second-lowest well-to-wheel greenhouse gas emissions intensity, with 2% (in the case of medium cars), to 37% more than battery electric vehicles (in the case of large cars). The well-to-wheel emissions of plug-in hybrids were estimated under the assumption that the utility factor (share of total annual mileage done in charge-depleting mode) was 64%, based on the range of plug-in hybrid models sold in 2019 and converting their utility factor under Japan's JC08 vehicle test to estimated utility factor in the Worldwide Harmonized Light-Duty Vehicles Test Cycle.

Fuel cell electric vehicles had the third-lowest well-to-wheel emissions intensity (in the two size segments where fuel cell vehicles were offered in 2019), at slightly below 140 g CO_2-eq/km.

[1] Other countries with even lower rated fuel consumption, including Denmark, France, Germany, Iceland, the Netherlands and Norway, have achieved very low emissions with stringent fuel economy policies and/or policies promoting the sales of electric vehicles.

Japan's gasoline and hybrid electric vehicles are amongst the lowest-emission conventional vehicles across major car markets

Rated well-to-wheel emissions of new light-duty vehicles sold in Japan, by size segment, 2019



Notes: The figure shows the top four light-duty vehicle segments, accounting for 93% of light-duty vehicle sales in Japan in 2019. An explanation of legends and acronyms is provided in the notes for Figure *Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019*. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 in Japan.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

Emerging markets and developing economies need to leverage efficiency technologies, including hybrids and zero-emission vehicles

Well-to-wheel emissions of light-duty vehicles sold in emerging markets and developing economies in 2019

The emerging markets and developing economies analysed here include Argentina, Brazil, Chile, Egypt, Malaysia, Mexico, Peru, the Philippines, the Russian Federation and Ukraine. Of the light-duty vehicles sold in 2019 in these countries, 99% were internal combustion engine vehicles: 82% gasoline and 17% diesel. The majority of the remaining 1% were hybrid electric vehicles. These numbers highlight the potential to capitalise on the affordability of hybrid electric vehicles in the coming decade in these countries.

As in every other region, battery electric vehicles and plug-in hybrids provided substantial emissions reductions potential in 2019, but that potential went largely unrealised, as sales shares of these vehicles were very low. The well-to-wheel greenhouse gas emissions reduction potential of battery electric vehicles and plug-in hybrids was 35% to 71% of the well-to-wheel emissions of gasoline internal combustion engine vehicles, depending on powertrain and segment.

Ensuring that developing regions contribute to and benefit from the emissions reduction potential of zero-emission vehicles will require special attention, above all in electrifying two-wheelers and urban transit buses, but also in promoting sales of battery electric vehicles and plug-in hybrids.

Projected well-to-wheel emissions of light-duty vehicles sold in emerging markets and developing economies in 2030

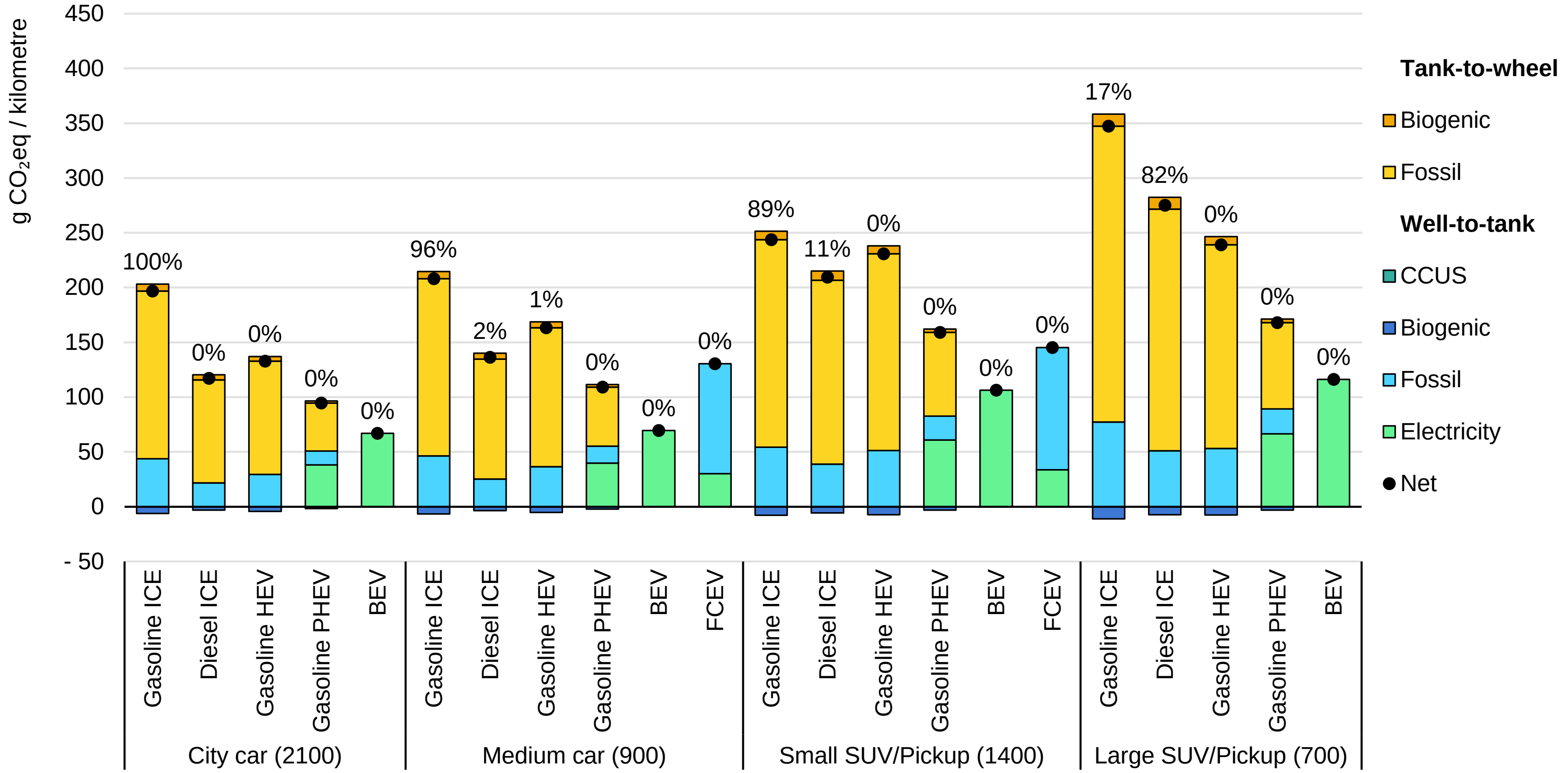
Several countries within the group of developing countries have weaker fuel economy standards than those of other regions, and some do not have them at all. Despite this, the well-to-wheel greenhouse gas emissions of internal combustion engines decline markedly (by 20% to 34% between 2019 and 2030 in the Stated Policies Scenario), reflecting the larger potential for efficiency technologies to reduce emissions from vehicles sold in these markets.

In addition, policies in emerging markets and developing economies to integrate renewables in electricity generation tend to be less ambitious, with fewer investments. While battery electric vehicles remain the least-emitting powertrain, their well-to-wheel emissions reductions are projected to fall by only 21% in light-duty vehicles between 2019 and 2030 in the Stated Policies Scenario.

The potential for well-to-wheels emissions reductions in fuel cell electric vehicles is modest in emerging markets and developing economies because projected well-to-tank emissions reductions in hydrogen are limited, and fuel cell electric vehicles are projected to be sold primarily in light commercial vehicle segments, which have higher fuel consumption than cars. cargo is used to fuel the LNG tanker. Taking into account the energy needed both to liquefy natural gas and to turn LNG back into gas, around 11% of the gas originally arriving at the liquefaction terminal is consumed.

The vast majority of light-duty vehicles sold in emerging markets and developing economies in 2019 were gasoline and diesel city and medium cars, and small SUVs

Rated well-to-wheel emissions of new light-duty vehicle sales across emerging markets and developing economies, by size segment, 2019

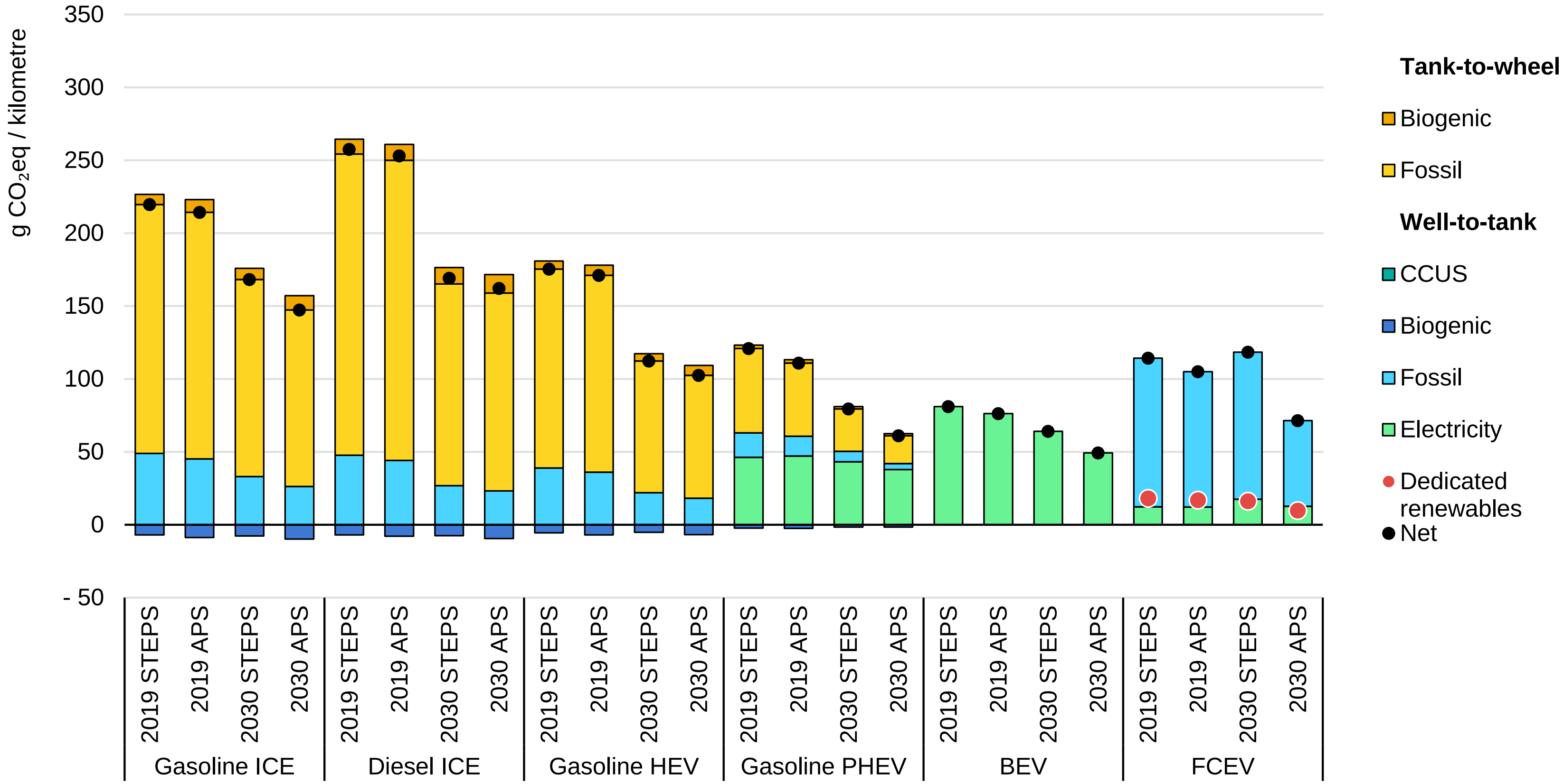


Notes: The figure shows the top four light-duty vehicle segments, accounting for 88% of light-duty vehicle sales in the developing countries in 2019. An explanation of legends and acronyms is provided in the notes for Figure *Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019*. Within each size segment, the figure shows the well-to-wheel greenhouse gas emissions for powertrains sold in 2019 in emerging markets and developing economies.

Sources: IEA analysis based on IHS Markit and the IEA Mobility Model (2021 September version).

Well-to-wheel greenhouse gas emissions improvements in emerging markets and developing economies depend on fuel economy standards

Rated well-to-wheel emissions of new light-duty vehicle sales in emerging markets and developing economies, 2019 and 2030



Notes: An explanation of legends and acronyms is provided in the notes for Figure Rated well-to-wheel emissions of new light-duty vehicle sales worldwide, by size segment, 2019.
Source: IEA Mobility Model (2021 September version).

The GFEI 2050 target for 90% fleet-wide reduction in light-duty vehicle well-to-wheel greenhouse gas emissions, and well-to-wheel emissions reductions in the IEA Scenarios

Existing fuel economy improvements to 2030 as they are reflected in the IEA Stated Policies Scenario are insufficient to meet the Global Fuel Economy Initiative (GFEI) target of doubling the rated fuel economy of new light-duty vehicle sales in 2030 relative to 2005. The Stated Policies Scenario incorporates all relevant current and stated policies, including fuel economy and CO_2 emissions standards, internal combustion engine phase-outs, and zero-emission vehicle sales targets. In contrast, fuel economy improvements required in the Announced Pledges Scenario to meet governments' announced climate ambitions slightly exceed the Global Fuel Economy Initiative's 2030 light-duty vehicle fuel economy targets. The improvements anticipated in the Announced Pledges Scenario would come about from legislation that aligns fuel economy standards with the level of ambition needed to achieve countries' nationally determined contributions to the Paris Agreement on climate change, and existing regional and national net zero emissions pledges. They would be realised by improving the engine, powertrain and vehicle efficiency of internal combustion engine vehicles and from increasing sales of zero-emission vehicles.

The Announced Pledges Scenario puts the world on a trajectory to reducing well-to-wheel greenhouse gas emissions reductions by nearly 40% by 2050, and hence falls far short of the Global Fuel Economy Initiative's long-term and even more ambitious target, to reduce well-to-wheel emissions by 90% by 2050 relative to 2005.

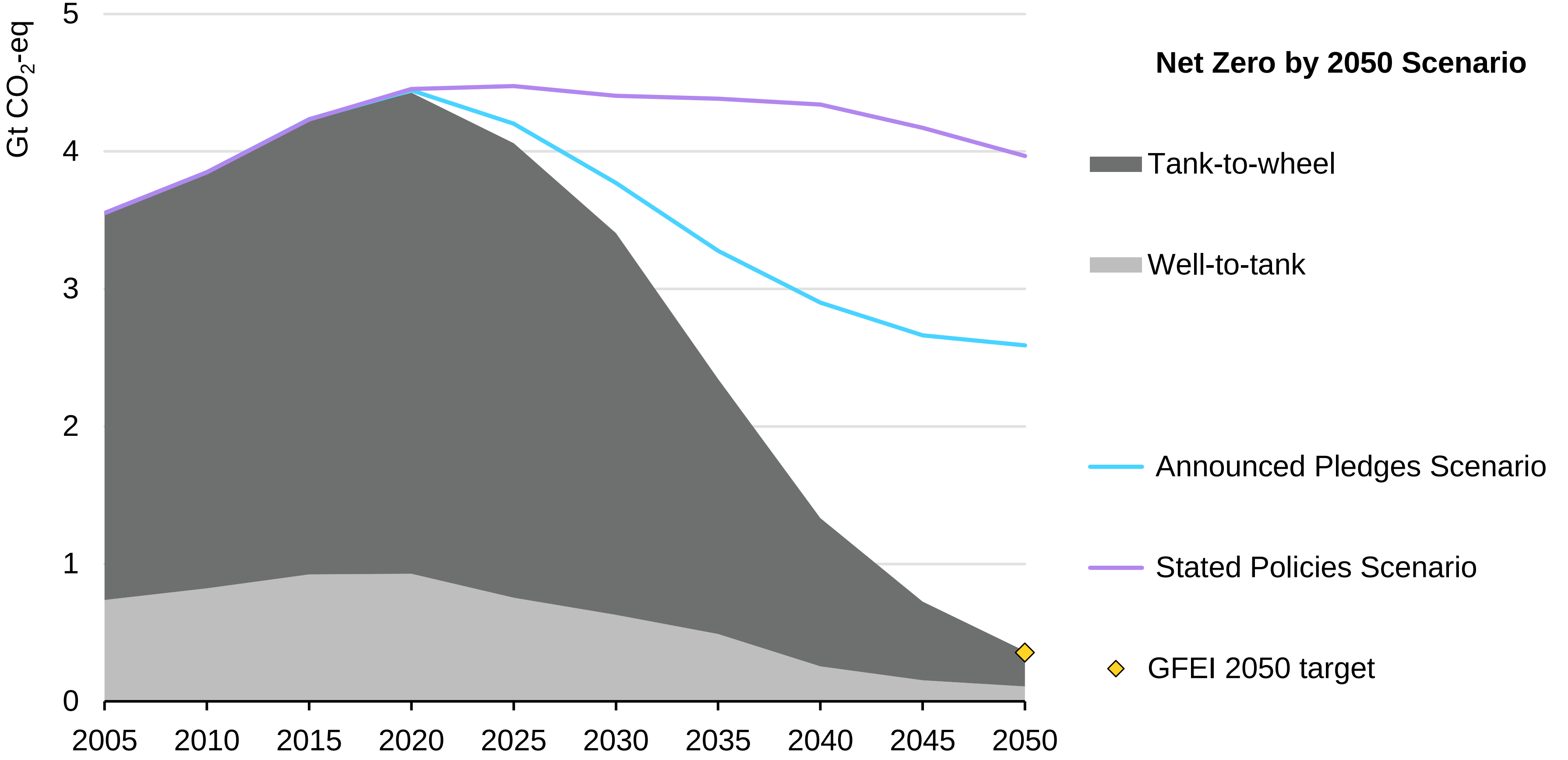
This target, designed by the initiative's partners to limit the global average temperature rise to 1.5°C relative to pre-industrial levels by 2100, requires an energy and transport sector transformation of the scale, speed and depth depicted in the IEA Net Zero by 2050 Scenario.

Of the IEA Scenarios, only the Net Zero by 2050 Scenario can achieve the Global Fuel Economy Initiative's long-term goals. This highlights the need for aggressive action on several fronts:

- improvements in vehicle efficiency, including in conventional internal combustion engine and hybrid electric vehicles, that go beyond those even of the Announced Pledges Scenario
- simultaneous rapid deployment of zero-emission light-duty vehicles, with all global sales of light-duty vehicles being zero-emission by 2035
- near complete decarbonisation of electricity and hydrogen supply chains that power zero-emission vehicles by 2050
- modal shift and travel demand management measures.

Meeting the long-term GFEI target of 90% reduction in well-to-wheel greenhouse gas emissions in light-duty vehicles between 2005 and 2050 requires the full range of policies included in the IEA Net Zero by 2050 Scenario

Global well-to-wheel emissions reductions in the light-duty fleet, GFEI target and IEA Scenarios, 2005-2050



Source: IEA Mobility Model (2021 September version).

Policy recommendations

Strong policies are needed to ratchet down the greenhouse gas emissions of light-duty vehicles to levels that achieve climate goals

Reductions in well-to-wheel greenhouse gas emissions since 2005 fall well short of the decline needed to achieve the targets of the Global Fuel Economy Initiative or meet the climate pledges that countries have made. Policy makers should focus on aligning fuel economy and/or CO_2 emissions standards with announced net zero emissions targets. They should ensure that regulations are based on and influence real-world performance, counter the trend towards larger, heavier vehicles, and harness the potential of zero-emission vehicles.

Progress on reducing emissions from supplying electricity and hydrogen is the foundation for decarbonising the whole energy sector and ensuring that zero-emission vehicles perform to their full potential. Broader implications of global vehicle production also must be considered to ensure that the automotive industry can contribute to climate goals, notably in harmonising fuel economy standards and other regulations, including vehicle import and export conditions to ensure that emerging markets and developing countries do not become dumping grounds for internal combustion engine vehicles.

Align fuel economy standards and electrification targets with climate pledges

The IEA Announced Pledges Scenario shows the improvements that would be needed in each country or region to ensure that light-duty vehicles contribute to climate targets. The gap in performance between the IEA Stated Policies Scenario and the Announced Pledges Scenario shows that current and stated policies are far from adequate to reach these ambitions. At a global level, only the IEA Net Zero Emissions by 2050 roadmap reaches the Global Fuel Economy Initiative target of reducing light-duty vehicle greenhouse gas emissions on a well-to-wheel basis by 90% by 2050, relative to their 2005 level.

To align emissions reductions in light-duty vehicles with climate pledges, countries need to nearly triple the pace at which vehicle efficiency technologies are adopted. This will require promoting efficiency technologies in conventional internal combustion engine vehicles and accelerating the market adoption of zero-emission vehicles.

Phase out fuel subsidies and tax road fuels at levels that reflect their health and climate impacts

Fuel taxes provide incentives for consumers to buy fuel-efficient vehicles, and to drive in a more efficient way. In European countries, Japan and Korea, where fuel taxes are high, the sales-weighted average fuel consumption of light-duty vehicles is amongst the lowest in the world. Fuel taxation also improves the prospects for hybrid electric vehicles and zero-emission vehicles, on the basis of the total cost of owning and operating a vehicle.

Implicit and explicit subsidies that reduce the costs of supplying oil and gas products to the road sector should be phased out rapidly. These fuels should be priced at levels commensurate with the health impacts of local pollutants (from tailpipe emissions) plus the well-to-wheel climate impacts of greenhouse gas emissions.

To ensure that these measures benefit citizens, revenues generated through such taxes can be transparently allocated, for example to transport infrastructure, including not only roads but also public transport and walking and cycling infrastructure. Targeted measures can ensure that people most severely affected by fuel taxation – such as farmers, rural people and small businesses – are compensated, that fuel taxes do not become a form of regressive taxation, and that taxation does not trigger popular discontent.

Keep your eye on the rear-view

For regulations to be effective, they must enable authorities to recognise, monitor and counter trends that threaten to undermine progress in reducing greenhouse gas emissions. Two of these trends, the steady increase in vehicle weights and sizes and the gap between tested and real-world emissions, need to be held in check, and ideally reversed, by regulatory action. A third regulatory question concerns the roles of hybrids and plug-in hybrids in reducing light-duty vehicle emissions and achieving climate targets. We argue for a nuanced approach that takes into account real-world benefits and trade-offs to ensure that hybrids and plug-ins contribute to, but do not delay, the achievement of decarbonisation goals. Below we outline promising policy approaches to these three issues.

Countries can draw upon policies to counter the growth in vehicle weight and power. Policies in France, Japan and Norway have helped to ensure that the light-duty vehicles sold in these countries are among the lightest and most fuel-efficient worldwide. In addition to aggressive fuel taxation, as well as CO_2 emissions and fuel economy standards, these countries either tax or provide subsidies (or other preferential treatment) to vehicles according to their weight, size, greenhouse gas emissions and pollutant emissions, or some combination of these performance attributes.

These policies have helped reduce average CO_2 emissions consistently each year. The policies show that curbing the shift to larger, heavier vehicles, promoting smaller, lighter vehicles, and ensuring higher market shares of hybrid and electric vehicles can make the Global Fuel Economy Initiative targets easier to achieve.

Real-world monitoring that informs future regulations and compliance frameworks can rely on digital technologies. To ensure that fuel economy and/or CO_2 emissions standards have their intended impact, continued monitoring is needed to bridge the gap between rated and real-world performance. One promising development is the passage of the EU Commission Regulation 2018/1832, which requires carmakers to install on-board fuel consumption monitors that enable over-the-air collection of real-world electricity and fuel consumption data, which can be made available to regulators in aggregated form.

Variability between rated and real-world performance is particularly wide in plug-in hybrid electric vehicles, as trip-making and charging behaviour can have a substantial impact on their real-world fuel economy, electricity demand and emissions of greenhouse gases and local pollutants. Regulations and fiscal policies on plug-in hybrids need to be more closely tied to their real-world performance and to promote charging and driving patterns that ensure these vehicles realise their potential to reduce emissions.

Regulatory mechanisms can encourage vehicle manufacturers to play an active role in ensuring that plug-in hybrid drivers are able to maximise the distance they drive using electric power. For example, fiscal and other incentives should favour plug-in hybrids with a high ratio of electric motor power to combustion engine power.

Harness the potential of zero-emission vehicles

A key finding of this report is that zero-emission vehicles, particularly battery electric vehicles, are the most efficient, cost-effective and sensible technology option for achieving deep reductions in well-to-wheel greenhouse gas emissions in the light-duty vehicles sector.[1] A broad suite of policies targeting vehicle manufacturers can accelerate the market adoption of zero-emission vehicles and ensure that they fulfil their potential to reduce emissions.

Vehicle efficiency standards are not technology-forcing per se, but once they become sufficiently stringent, they require manufacturers to shift sales shares from internal combustion engine vehicles to hybrid electric vehicles, and from there to zero-emission vehicles. Assuming that they are politically attainable and credible, zero-emission vehicles sales requirements, and/or internal combustion engine phase-outs enshrined in regulations, provide more certainty for investors in various parts of the electric vehicle ecosystem seeking to develop the infrastructure and technologies needed to shift to electromobility.

While fuel economy standards and zero-emission vehicle sales mandates (or internal combustion engine phase-out targets) can reinforce each other, explicitly linking the two carries the risk of

[1] A complete assessment of the impacts of shifting to battery and fuel cell electric vehicles will require extending the analytical scope to the entire vehicle life cycle, as the International Council on Clean Transportation did recently in its global life-cycle greenhouse gas comparison report. The IEA will continue to refine its data and in the coming year will release an online, interactive tool that enables users to compare the performance of different fuel-powertrain vehicle combinations, for vehicles sold both today and under future policy scenarios.

creating a regulatory loophole. When the two approaches are linked, the result is often a reduction in the stringency of standards: incentives for zero-emission vehicle sales that generate compliance credits effectively relax fuel economy requirements for a manufacturer's remaining fleet. Phasing out multiple credits for zero-emission vehicles in markets where electric vehicles have already attained higher market shares can close this loophole.

Battery electric vehicles already achieve the world's lowest well-to-wheel greenhouse gas emissions and are projected to continue doing so through to 2030, perhaps complemented in some regions by fuel cell electric vehicles. Aggressive measures will be required to further promote zero-emission vehicles, which previous IEA reports have shown to be the most technically viable and cost-effective way to achieve deep well-to-wheel greenhouse gas emissions reductions in the light-duty vehicle sector – and especially to reach the Global Fuel Economy Initiative 2050 target and the emissions reductions projected in the IEA Net Zero by 2050 Scenario.

Seek to harmonise standards beyond the national level

International harmonisation of standards can lower the cost of implementing and enforcing regulations such as fuel economy standards. Such co-operation also provides a valuable basis for engagement to achieve broader societal and environmental goals, including climate objectives.

Work is being undertaken by major economies, and in particular co-operation between the European Union and the United Nations Economic Commission for Europe under the World Forum for Harmonisation of Vehicle Regulations, known as WP 29. The result is a framework in which emerging markets and developing countries have been able to more easily and cost-effectively adapt test cycles (like the New European Driving Cycle and more recently the Worldwide Harmonized Light-Duty Vehicles Test Procedure) and other procedures. This framework has also focused on harmonising regulation across a wide array of aspects related to vehicles, including safety, pollution and digitalisation.

Ensure that emerging markets and developing countries do not become dumping grounds for internal combustion engine vehicles

Developed countries have put in place the most ambitious fuel economy and zero-emission vehicle targets. As these countries transition away from conventional gasoline and diesel vehicles, policy action is needed to ensure that emerging markets and developing countries do not become a dumping ground for internal combustion engine vehicles. Such action includes international co-operation, monitoring of used vehicle trade flows and regulation.

Emerging markets and developing countries can seize upon the opportunities presented by the transition to electromobility by identifying parts of the electric vehicle ecosystem that match their economic, industrial and energy goals and their competitive advantage. For instance, growth in mineral demand for electric vehicle batteries can boost national development in several emerging markets and developing countries, if supported by policy frameworks that protect citizens strongly.

In some developing countries, however, there may be a transitional role for policies that promote the purchase of hybrid electric vehicles. Hybrid electric vehicles are cheaper than battery electric vehicles and in some countries the grid may not be stable enough – and electric vehicle chargers plentiful enough – to handle a rapid uptake of electric vehicles.

Design a portfolio of policies to address emissions throughout the life cycle

Although it is critical that policy makers and regulatory bodies are aware of the well-to-wheel (and even broader life-cycle) greenhouse gas emissions impacts of road vehicle production and operations, attempting to adopt a single policy to regulate activities across the fuel and vehicle supply chain is not advisable. Specific policy instruments can best promote improvements in each of the many regulated industries involved in the fuels and vehicles supply chains. While no single entity can deploy technologies to reduce the carbon intensity of various stages of fuel supply, across the diverse fuel options, targeted policies can spur improvements at various stages by industrial actors throughout the fuel supply chain.

Designing and enforcing separate but in some cases mutually reinforcing (or overlapping) regulatory and fiscal instruments for different stages of the life cycle are the most promising means to achieving the rapid action needed. Within the scope of the fuel supply chain (well-to-tank), different policies are appropriate to integrate renewables and decarbonise electricity, depending on the current status and mix of electricity generation and energy storage, such as renewable portfolio standards and feed-in tariffs. Building on the success of California's low-carbon fuel standard, more and more policies have begun to explicitly target reductions in the carbon intensity of fuel supply. Similar provisions have been adopted in Canada (Clean Fuel Standard), Brazil (RenovaBio) and Europe, with the latest revisions proposed to the Renewable Energy Directive II under the Fit for 55 package.

Annexes

Annex 1

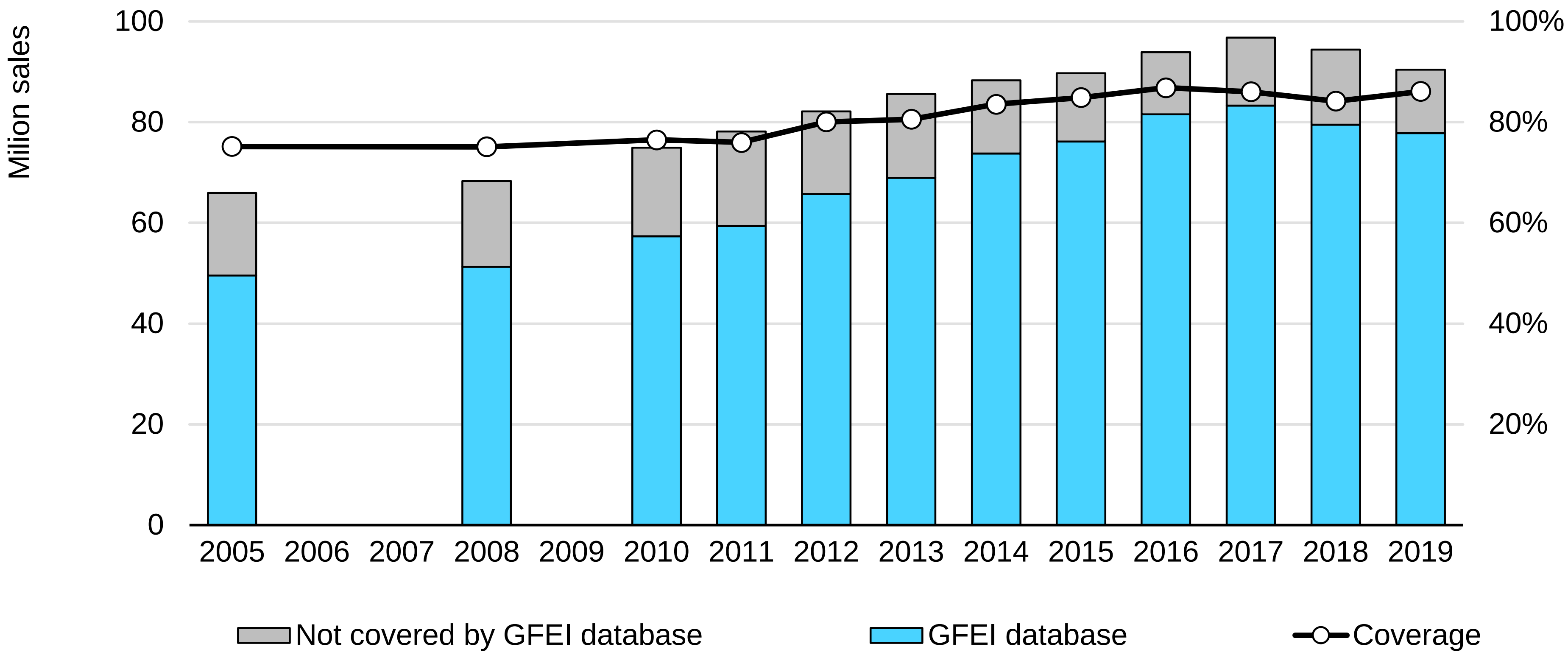
Methodology: Light-duty vehicle fuel economy analysis

The IEA-Global Fuel Economy Initiative (IEA-GFEI) database used for this report is a multi-year dataset. It is based on information from the IHS Markit databases (released in 2005, 2008 and every two years since 2010) and additional information extracted from numerous vehicle specification sources. The IHS Markit databases contain information on the number of vehicles registered at the model level, as well as characteristics such as drivetrain, engine volume and power, valves per cylinder, fuel and transmission type, turbocharging, empty weight, fuel economy, and CO_2 emissions per kilometre. The complementary technical sources facilitated the integration of additional inputs into the IEA-GFEI database. These inputs were integrated hierarchically at the model level or at lower disaggregation levels (depending on the details available), starting with the models with the broadest market coverage and reaching at least 80% of all markets and all parameters discussed in this report.

Three test cycles are applied worldwide to measure specific fuel consumption (litres of gasoline equivalent per 100 kilometres) or fuel economy (miles per gallon or kilometres per litre of gasoline equivalent): the European Union New European Driving Cycle (NEDC), the US Corporate Average Fuel Economy (CAFE) and the Japan Cycle ’08 (JC08). The Worldwide Harmonized Light-Duty Vehicle Test Procedure (WLTP) and its related test cycle (WLTC) have been advanced (and are being refined) to replace region-specific approaches with a harmonised testing scheme. For this report, results of region-specific tests were converted using equations advanced by the International Council on Clean Transportation (2014).

The global coverage is estimated against sales values from the International Organisation of Motor Vehicle Manufacturers (Organisation Internationale des Constructeurs d'Automobiles [OICA]), which provides the most comprehensive and publicly available information on global sales volumes, including both light- and heavy-duty vehicle sales. The GFEI database has always covered more than 75% of the total vehicle market. Since trucks and buses account for around 5-10% of the total, the GFEI database covers more than 80% of total light-duty vehicle sales.

GFEI database coverage of global vehicle sales (including light- and heavy-duty vehicles)



Sources: IEA analysis based on the IHS Markit database, OICA (2021).

List of countries included in the dataset.

Countries included with complete time-series 2005-2019									
Argentina	Australia	Brazil	Canada	Chile	China	Egypt	France	Germany	India
Indonesia	Italy	Japan	Korea	Malaysia	Mexico	Peru	Philippines	Russia	South Africa
Turkey	Ukraine	United Kingdom	United States						

Countries included but with incomplete time-series									
Austria	Belgium	Bulgaria	Croatia	Cyprus	Czech Republic	Denmark	Estonia	Finland	Greece
Hungary	Iceland	Ireland	Latvia	Lithuania	Luxembourg	Macedonia	Malta	Netherlands	Norway
Poland	Portugal	Romania	Slovakia	Slovenia	Spain	Sweden	Switzerland	Thailand	Poland

Annex 2

Methodology: Well-to-wheel analysis

revious IEA publications, including the Global EV Outlook 2019 and The Role of Critical Minerals in Clean Energy Transitions, compared the emissions incurred by different light-duty vehicle powertrains on a full life-cycle basis. Chapters 3 and 4 of this report focus on integrating and modelling the well-to-wheel emissions into the IEA's long-term transport modelling tool, the IEA Mobility Model.

Future work will build on this initial analysis to explore fuel supply pathways in greater detail, investigating regional variability and how the pathways might evolve in the IEA Scenarios. It will also incorporate analysis on vehicle-cycle emissions, thereby extending the analytical scope to the entire life cycle.

For this future work, analysts in the IEA Secretariat aim to collaborate with experts in the Technology Collaboration Programmes assembled under the Transport Coordination Group,[1] and researchers at Argonne National Laboratory in the United States working on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model (GREET).

Treatment of greenhouse gases

The major greenhouse gases associated with fuel supply chains (CO_2, methane, nitrous oxide), are covered in each pathway, and a broader set of greenhouse gases is considered in the processes that draw from GREET, developed by the Argonne National Laboratory in the United States. In the IEA Mobility Model, tank-to-wheel coverage is limited to CO_2 emissions from fossil and biogenic fuel combustion; inclusion of other greenhouse gases is a high priority for future development.

[1] The seven Technology Collaboration Programmes (TCPs) working on transport-related topics are the Advanced Fuel Cells (AFC TCP), the Advanced Motor Fuels (AMF TCP), the Clean and Efficient Combustion TCP, the Hybrid and Electric Vehicles (HEV TCP), the Advanced Materials for Transportation (AMT), the Bioenergy TCP and the Hydrogen TCP.

Oil products

Data

Country-level time-series data on energy production, transformation and use, as well as greenhouse gas emissions from energy, are reported by national statistical and energy agencies (among others) and compiled by the IEA Energy Data Centre into the World Energy Balances. Drawing on these and other data and modelling tools (see below), the IEA World Energy Outlook division analysed energy inputs for oil production and refining to estimate the associated emissions at the country level. Results of this analysis are outlined in the 2018 World Energy Outlook.

The emissions intensities of crude oil extraction are based on a field-by-field dataset produced by the King Abdullah Petroleum Studies and Research Center using the Oil Production Greenhouse Gas Emissions Estimator (OPGEE, version 2.0b). The World Energy Outlook emissions estimates take a co-product displacement approach, which applies an emissions credit to the primary operation equal to the energy that would have otherwise been required to produce the co-product.

The data include different types of crude oil (e.g. heavy, medium, light and sweet, sour). Heavy and sour crude oil generally require more energy to process. The refining modelling includes assumptions on simple and complex refinery configurations.

Hydrogen needs in refining operations are estimated using the Petroleum Refinery Life Cycle Inventory Model (PRELIM), a detailed process-based refinery modelling tool.

Techno-economic, policy and market dynamics form the basis for projections in the efficiency improvements that these processes realise in the Stated Policies Scenario and the Announced Pledges Scenario. That analysis, performed within the World Energy Model, is the basis for the well-to-tank emissions reported here. The data include emissions from oil extraction, crude transport, refining and product transport. The data also describe the quantity and associated emissions by regions of production and of consumption, at different levels of aggregation. Refining activities and efficiencies are based on projections in the World Energy Outlook 2020.

Methodology

The World Energy Outlook model reports on 26 World Energy Model regions and at the global level. For countries modelled as part of a broader region, emissions factors are assumed to be the same as those for the encompassing region. For crude oil trade balances, gross export and import requirements are determined by comparing domestic production and refinery consumption in each region. Transport of crude oil is split between pipeline and seaborne trade, based on major interregional pipelines. Projections of energy and emissions intensities account for continued technological improvements (which tend to reduce the energy intensity of production) and resource depletion (which tends to increase the energy intensity).

As hydrogen consumption in refineries is a major source of emissions, regional hydrogen demand for regions is estimated using PRELIM. This estimate is based on the sulphur content of various types of crude oil and the sulphur content allowed in final products. In the Stated Policies Scenario, steam methane reforming using natural gas represents the majority of hydrogen production for use in refineries. In the Announced Pledges Scenario, electrolytic production (using renewables) or steam methane reforming with carbon capture, utilisation and storage (CCUS) gain much larger shares.

Refining emissions are allocated to each product using scaling factors derived from the study by Sun et al. (2019), which calculated total refining and product-level emissions intensity using PRELIM. The emissions factor from the producer perspective represents the emissions where oil production and refining take place. The emissions factor from the consumer perspective corresponds to emissions from domestically refined crude and imported crude.

Refining emissions are influenced by the type of crude oil produced. More complex refinery configurations are needed to process high-density (heavy) and high-sulphur (sour) crude into petroleum products, than low-density (light), low-sulphur (sweet) crudes. Hydro-skimming is the most basic refinery configuration and is generally applied in refining light, sweet crude oil. In contrast, medium conversion refineries can refine light-sweet to medium-sour crudes. Deep conversion refineries, which use hydrocracking and coking, can refine medium to heavy, sour crudes.

The most carbon-intensive parts of refineries are stationary fuel combustion units (e.g. steam boilers, process furnaces and process heaters), used to heat crude oil for processing activities. Since more processing is required to convert heavier crudes into petroleum products, medium and deep conversion refineries are more energy-intensive. Medium and deep conversion refineries also require hydrogen to lower the sulphur content of heavy, sour crudes.

Hydrogen is typically produced via steam methane reformers or sourced as a by-product from chemical plants. Steam methane reforming is an energy-intensive process with high emissions. Fuel combustion energy for processing increases by 61 MJ/m^3 for each 1 kg/m^3 sulphur and 44 MJ/m^3 for each 1 kg/m^3 density of crude refined. Deep conversion refining has the highest global volume-weighted average carbon intensity (47.5 kg CO_2-eq/barrel to 52.1 kg CO_2-eq/barrel), followed by medium conversion (36.3 kg CO_2-eq/barrel) and hydro-skimming (17.3 kg CO_2-eq/barrel).

Regional variations in the carbon intensity of refining stem from differences in the complexity and vintage of refineries and the quality of crude oil available. Generally speaking, crudes originating in Asia (excluding the People's Republic of China [hereafter, "China"]), Europe, Africa and Oceania have lower refining emissions due to the quality of crude, compared with crude produced in North America and Latin America. Deep conversion dominates oil refining in China, which has a refining carbon intensity of 50.0 kg CO_2-eq/barrel, and in India (50.4 kg CO_2-eq/barrel) and the United States (44.4 kg CO_2-eq/barrel). Where medium conversion refining is primarily employed, refining carbon intensities range from 37.1 kg CO_2-eq/barrel in Japan to 40.3 kg CO_2-eq/barrel in South Korea and 41.4 kg CO_2-eq/barrel in Germany. The Russian Federation has a low refining carbon intensity (33.9 kg CO_2-eq/barrel) because it relies on hydro-skimming and medium conversion refining. While fuel gas, which is a by-product off-gas from refining, is the primary fuel used by refineries, off-site electricity generation also contributes to the carbon intensity of refining.

Limitations and future improvements

The energy and emissions related to infrastructure, such as those for manufacturing the drilling rigs or the steel used in wells or pipelines, are not included. These amounts are not readily available in energy statistics and are small in comparison with the process emissions. Land-use CO_2 emissions from clearing areas for production facilities in onshore areas are uncertain and also excluded from the analysis.

Currently, emissions incurred during seaborne transport of oil are based on static emissions factors. Future improvements could incorporate the modelling included in scenario projections of fuel switching and efficiency improvements in oil tankers. Omission of this linkage is expected to have only a minor impact on the carbon intensity estimates, however, and is likely within the margin of precision for the estimates reported, as current transport emissions represent only 5% of total well-to-tank emissions.

As more detailed trade and refinery data become available, the modelling can be updated to better capture country-level emissions factors. For example, a better understanding of site-specific refinery configurations would enable a more rigorous approach to allocating refinery emissions to oil products based on the unit processes and their respective combustion emissions, as is done in dedicated refinery process-level modelling such as PRELIM and GREET.

Natural gas

Data

As with well-to-tank emissions associated with oil production, the IEA World Energy Outlook division relied upon energy balances and greenhouse gas emissions to analyse historical country-level time series of well-to-tank emissions of natural gas, as outlined in the 2018 World Energy Outlook. That analysis, performed within the World Energy Model, is the basis for the well-to-tank emissions described here. The estimates include emissions of production, processing, transmission and distribution of gas. Several sources were used to estimate the energy intensity of gas production, including the GHGenius model, and data collection efforts and collaborations mobilised to develop the IEA methane tracker.

Methodology

The World Energy Outlook team models emissions for 26 World Energy Model regions and at the global level. For countries modelled as part of a broader region, the emissions factors are assumed to be the same as those provided for the encompassing region.

The World Energy Outlook emissions estimates take a co-product displacement approach, which applies an emissions credit to the primary operation equal to the energy that would have otherwise been required to produce the co-product.

Projections of energy and emissions intensities account for continued technological improvements (which tend to reduce the energy intensity of production) and resource depletion (which tends to increase the energy intensity). In the Stated Policies Scenario, efficiency measures that have positive net present value are assumed to be adopted gradually around the world to 2040. In addition, various targets and initiatives to reduce methane emissions from oil and gas operations, primarily in North America, are taken into consideration. In the Announced Pledges Scenario, regions or countries with announced net zero pledges are assumed to employ all available methane mitigation technologies, even those that do not have a positive net present value, reducing methane emissions by 75% by 2030.

Emissions intensities of liquefied natural gas (LNG) are calculated for all natural gas that is liquefied (i.e. has emissions associated with liquefaction in the World Energy Outlook dataset). The emissions intensities of compressed natural gas (CNG) are calculated based on the complete dataset, which includes the flows that are liquefied and regasified.

Limitations and future improvements

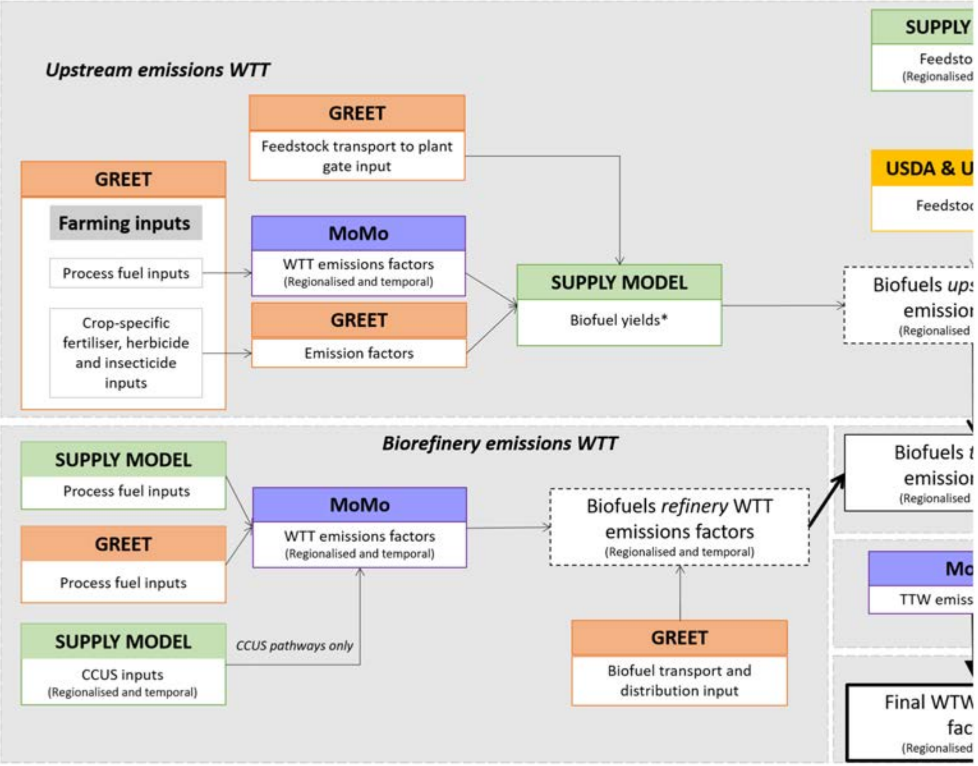
The majority of the natural gas that is liquefied is done so for transport purposes, and not actually consumed as LNG. Thus, the LNG emissions factors are likely to have been overestimated because regasification is included. The calculated intensities of CNG should also exclude the portion that is consumed directly as LNG, though this is expected to have a negligible impact based on current consumption patterns.

As with other pathways, energy and emissions related to infrastructure, which are expected to be small with respect to total well-to-tank impacts, are not included due to data limitations. Land-use CO_2 emissions from clearing areas for production facilities are also excluded from the analysis due to limited data and high uncertainty.

As with crude oil and oil production, emissions from seaborne transport are based on static emissions factors. Future improvements could reflect fuel switching and efficiency improvements as modelled in scenario projections in the ships that carry LNG.

Biofuels

Data sources used to calculate biofuels well-to-tank emissions factors



Notes: WTT = well-to-tank; WTW = well-to-wheel; TTW = tank-to-wheel; GAIN = Global Agricultural Information Network. Colour-coded boxes indicate the data source: orange = GREET; purple = MoMo (IEA Mobility Model); green = IEA Energy Technology Perspectives (ETP) supply model; yellow = United States Department of Agriculture (USDA).

Data sources

Several main data sources were used to calculate well-to-tank emissions factors. Emissions associated with feedstock cultivation, including fuel inputs and fertiliser, pesticide and insecticide application, were taken from GREET (2020 version). Biofuel yields and well-to-tank emissions factors for fossil fuels were taken from IEA ETP supply modelling, and calculated based on ETP modelling in the IEA Mobility Model.

Current feedstock shares for sugar, starch and lignocellulosic ethanol; for biodiesel; and for biomethane were taken from the 2020 USDA Biofuels GAIN reports and USDA data. Country-specific GAIN reports provide data on feedstock used for biofuels production across the major biofuels producing/consuming countries and regions, including Argentina, Brazil, China, the European Union, India and Indonesia. US-specific feedstock information was taken from data tables reported by US Bioenergy Statistics.

Where data were not available in a primary source, other sources were used to fill gaps. USDA GAIN reports complemented gaps when feedstock shares were not available in the ETP supply model, e.g. for food-based feedstocks such as virgin vegetable oils and starch/sugar-based ethanols. Input fuels used in the conversion of processed feedstocks to biofuel products (e.g. in biorefineries and gasifiers) were taken from the ETP supply model results, except in cases where more detailed and up-to-date modelling of processes was available in GREET. This approach was adopted for starch- and sugar-based ethanols to allocate electricity credits and to estimate the use of biomass process fuel inputs.

Yield differences were noted between GREET and ETP supply model results, which affected well-to-tank values. ETP supply model results for cellulosic ethanol, biomass gasification and Fischer-Tropsch synthesis (bio-FT) and biomethane could initially be more conservative, but improved to surpass GREET values, which remained static. Other yield comparisons, such as those for sugar and starch ethanol, fatty acid methyl ester (FAME) and hydrogenated vegetable oil (HVO) varied based on feedstock. For example, soybean to FAME/HVO yields were more conservative in the ETP supply model results than in GREET, as well as corn to ethanol yields.

Well-to-tank modelling in the IEA Mobility Model enables the user to specify which co-product allocation method to adopt for each biofuel production technology. Four scenarios were used: energy-based, blended (energy allocation for energy co-products and mass allocation where available for non-energy products), default settings in GREET (a combination of mass, energy and market value based allocations) and combined (using the most conservative value, except for corn stover and waste oil). The estimates reported in the main report use the combined allocation setting.

In ETP modelling, CCUS is applied to technologies that emit a pure stream of CO_2 during fuel synthesis. CCUS pathways consider the additional electricity inputs needed to capture and store CO_2, and account for the capture rates achievable via various pathways.

Direct and indirect land-use change emissions estimates were taken from the GREET CCLUB LUC add-on (Carbon Calculator for Land Use and Land Management Change from Biofuels Production) and the GLOBIOM report commissioned by the European Commission.

Methodology

- The biofuels production pathways added to the IEA Mobility Model are listed below. Pathways where CCUS is also considered are noted (i.e. "+ CCUS").
- **ethanol**: corn (starch) + CCUS; grain sorghum (starch) + CCUS; sweet sorghum (sugar) + CCUS; sugar cane (sugar) + CCUS; miscanthus (lignocellulosic) + CCUS; switchgrass (lignocellulosic) + CCUS; corn stover (lignocellulosic) + CCUS; forest residues (lignocellulosic) + CCUS
- **biodiesel FAME**: canola oil; soybean oil; palm oil; waste oil
- **biodiesel HVO**: canola oil; soybean oil; palm oil; waste oil
- **biodiesel–Bio-FT**: miscanthus + CCUS; switchgrass + CCUS; corn stover + CCUS; forest residues + CCUS
- **biomethane-anaerobic digestion**: animal waste + CCUS; wastewater sludge + CCUS; municipal solid waste + CCUS
- **biomethane-gasification**: forest residues + CCUS.

Region- and time-variant well-to-wheel emissions of input fuels used in cultivation, transport and conversion processes were estimated, and emissions factors were adopted according to lower heating value (for mobile equipment such as tractors and harvesters) or higher heating value (for stationary process, e.g. in biorefineries) as appropriate. Emissions factors of biomass and liquefied petroleum gas inputs were assumed to be region- and time-invariant, due to data limitations and for the sake of simplicity.

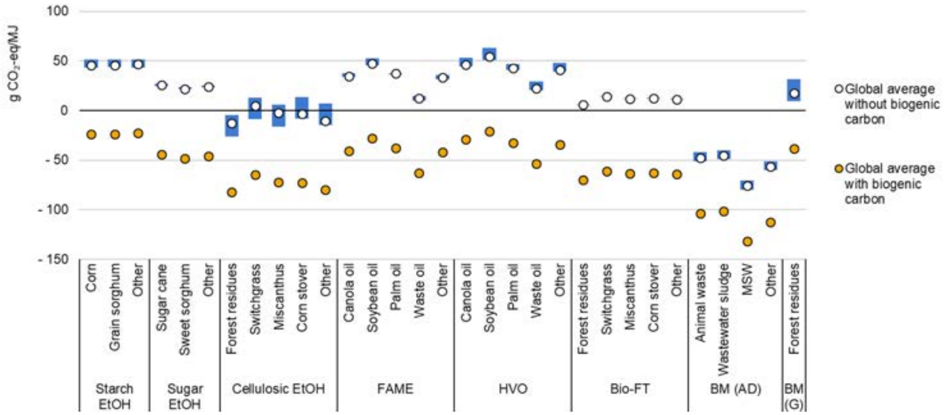
Emissions associated with fertiliser, herbicide and insecticide were taken directly from GREET and were not assumed to vary by region or over time – this could be corrected in future work to account for differences in regional application rates and by estimating the potential reductions in energy use and emissions incurred in producing these inputs.

Default GREET inputs were taken for transport emissions of the feedstock to the plant gate (biorefinery or site of conversion). For lignocellulosic feedstocks, an electricity co-product credit was allocated based on grid electricity and hence varied by time and region. In cases where the grid was assumed to have a negative well-to-wheel emissions factor (i.e. for cleaner decarbonised grids with CCUS technologies) it was assumed that no electricity credit was provided. As with all other electricity inputs, region- and time-variant grid electricity carbon intensities were applied in estimating the emissions incurred to power CCUS. The treatment of biogenic emissions is detailed in the final section of Annex 2 (on [biogenic CO_2 accounting]).

The well-to-tank carbon intensity of each feedstock-conversion pathway was calculated for in the Stated Policies Scenario and the Announced Pledges Scenario.

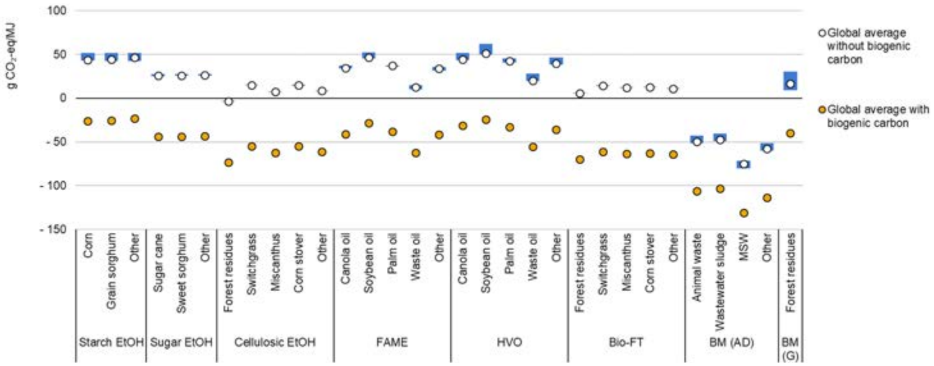
When comparing these with the figure titled "Regional variation and global average carbon intensity across feedstock specific biofuel pathways in 2020" in chapter 3, it can be seen that minimal changes occur within the specific feedstocks themselves, with global averages for the Announced Pledges Scenario slightly lower than for the Stated Policies Scenario. This is due to greater carbon intensity reductions from process fossil fuel use.

Regional variation and global average carbon intensity across feedstock specific biofuel pathways in the Stated Policies Scenario, 2030



Notes: EtOH = ethanol; LCE = lignocellulosic ethanol; BM = biomethane; AD = anaerobic digestion; MSW = municipal solid waste; G = gasification.

Regional variation and global average carbon intensity across biofuel pathways in the Announced Pledges Scenario, 2030



Limitations and future improvements

As the GREET model is based on agriculture practices in the United States, many of the default inputs are likely to be not representative for other countries and regions. These include fuel use types and intensities; pesticide, fertiliser and insecticide application rates; and transport and distribution modes and distances.

Projections of the emissions associated with farming operations currently consider gasoline, diesel and natural gas inputs from fossil sources only. In fact, the liquid and gaseous blends (i.e. gasoline + ethanol, diesel + biodiesel, fossil gas + biomethane) should be considered as used in the farm equipment, for consistency.

Regional and temporal variations in fertiliser and pesticide application rates would also be a helpful addition to the analysis as these are currently considered static over region and time. Analysis soon to be published by the IEA, together with other sources, could serve as a strong basis for such projections.

A dedicated literature review could be conducted to inform feedstock- and pathway-specific emissions intensity estimates, for instance for sugar beet ethanol and jatropha biodiesel. Consideration of more feedstocks for gasification-based biomethane would improve the analysis. Currently only forest residues are analysed.

Incorporating more recent data on biorefinery or other conversion processes would help to provide more accurate and precise regional estimates, as well as a basis for estimating efficiency improvement potentials. For instance, the use of biomass for power throughout the biorefinery process is currently treated as static over time, but improvements in stationary equipment or the use of low-carbon biomass during the process could reduce conversion emissions.

Further research to estimate and validate scenario projections of feedstock shares could help to inform the potential for emissions reductions, particularly for starch and sugar ethanols, as well as for vegetable oils for FAME and HVO. While historical data are available for some regions, greater clarity about projections based on policy announcements and developments at a feedstock-specific level would add rigour to current projections.

Direct and indirect land-use change factors were taken from a study focusing on the European (GLOBIOM) or US (GREET) context, and from policy and modelling scenarios that are not in the Stated Policies Scenario and Announced Pledges Scenario. Since they rely on coupled physical economy models (often partial or general equilibrium models), indirect land-use change estimates are highly uncertain, and the results vary widely depending on assumptions and the model used. This variability means that the modelling disconnect between MoMo and the models from which these indirect land-use change estimates are sourced is likely to be of secondary importance, and also that these estimates should be treated as order-of-magnitude estimates.

Electricity

Data sources

Using the data submitted by national administration offices for the IEA World Energy Balances, the IEA Energy Data Centre (EDC) produces and annually updates estimates of the carbon intensity of electricity at the plant gate and final electricity (accounting for plant own-use and transmission and distribution losses) for more than 160 countries. The time series extends back to 1990, and each year, the data are updated and extended to year-1 (i.e. in 2021 the data coverage spans until 2020) for OECD member countries, and year-2 for non-OECD members. The EDC data do not include upstream emissions, for example from natural gas extraction or coal production. Instead, upstream emissions data come from World Energy Outlook modelling and GREET.

The carbon intensity of electricity is expressed in grammes of CO_2 equivalent per kWh (g CO_2-eq/kWh), and uses 100-year global warming potentials (GWPs) to account for emissions other than CO_2, notably methane and nitrous oxide. GWPs from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) are used to convert to g CO_2-eq/kWh.

Electricity generated in one country may not be entirely consumed in that country, as electricity is often exported to neighbouring countries. To account for electricity trade, carbon intensities may be adjusted based on the share of electricity that is exported or imported compared with domestic production. However, the data needed to calculate such adjustments – the breakdown of electricity imports by trade partner – are available only for OECD member countries.

Methodology

As EDC's carbon intensity of electricity only covers year-1, the data for 2020 are based on preliminary estimates developed for the 2021 Global Energy Review.

The carbon intensity of electricity generation is determined as the ratio of total emissions from fossil fuels consumed for electricity generation (in both electricity-only and co-generation[1] plants) and the output of electricity generated from all fossil and non-fossil sources. Both main activity producers and autoproducers have been included in the calculation.

For co-generation plants, calculating the emissions for electricity-only generation from the IEA energy balances requires allocating

[1] Co-generation refers to the combined production of heat and power.

emissions between electricity and heat. The IEA adopts the fixed-heat-efficiency approach, which consists of fixing the efficiency of heat generation to compute the input to heat, and calculating the input to electricity as a residual from the total input. The standard heat efficiency assumed is that of a typical heat boiler, 90% higher heating value. This is different from the proportionality approach, which would allocate inputs based on the proportion of electricity and heat in the output and would be equivalent to assuming that the efficiencies of power and heat generation are equal.

As IEA accounting follows the convention of the United Nations Framework Convention on Climate Change (UNFCCC) of considering biogenic emissions as carbon-neutral, biogenic emissions in biomass-based electricity generation are not considered in this analysis. Electricity from the renewable fraction of waste is assumed to produce zero emissions, while electricity from the non-renewable fraction has an emissions factor in line with the 2006 IPCC Guidelines. Nuclear and renewable electricity generation are considered as producing no emissions.

As with all other fuel supply pathways, this analysis does not consider the emissions embodied in the construction, maintenance, operation (other than combustion of fossil fuels) and decommissioning of electricity generation (including power plants, solar PV installations, hydroelectric dams, wind turbines, etc.) and transmission and distribution infrastructure.

Upstream emissions associated with fuel inputs are estimated based on average plant efficiency and feedstock emissions intensities. For natural gas power generation, regional and temporal emissions factors described above are used. For other feedstocks (oil, coal, uranium and biomass), GREET default values are used across regions and time. It is assumed that there are no upstream emissions associated with non-biomass renewable power generation – that is, from solar, wind, hydropower and geothermal sources.

In estimating energy losses from electricity generation to final point of use, the electricity required for regular operations at power plants ("own-use") is deducted. A fraction of the electricity generated is lost while being transmitted and distributed to the consumption point, mainly through conversion into heat via the Joule effect. These transmission and distribution losses usually range between 5% and 15%, depending on the status of the power distribution system.

When analysing electric vehicles, electricity losses also occur during charging, at the site of the electric vehicle supply equipment (EVSE). The EVSE losses depend mainly on the power rate of the charger: the higher the power rate, the higher the losses. For this study, EVSE losses are assumed to be 5%.

Future improvements

Upstream emissions associated with the production and delivery of feedstock vary by region and over time; in the modelling here, this is currently the case only for natural gas. For example, the upstream emissions intensity of coal is assumed to be static for all regions. Future work should consider the variability in coal types and mining methods across regions.

In addition, plant efficiency is currently from the GREET model. Future work should align with supply model assumptions on the regional and temporal efficiency of plants. For example, uranium inputs are based on GREET assumptions for light-water reactors (specifically pressurised water reactors); including regional variation in nuclear power plant type would improve this analysis.

The carbon intensity of electricity used for this study is based on the annual weighted average emissions. The approach adopted here calculates the carbon intensity as the ratio between the total annual emissions from fossil fuel combustion for electricity generation and the total annual electricity produced over the year. This approach has several limitations. It assumes that national average electricity mixes are representative of regions where electric vehicles are charged (especially relevant in large countries with a wide variation of power generation mixes). It neglects the fact that electric vehicles are generally charged overnight, when the generation mix differs reliably from the average mix. And it does not consider the carbon intensity of the marginal technologies used to generate electricity.

An alternative to the annual average approach is a marginal approach that would not consider total annual values, but only the emissions and electricity production from the marginal power plant – the last dispatched plant or the one that produces the last kilowatt-hour of electricity demanded. A potential, if data-intensive, improvement would consist of adding estimated carbon intensities to the IEA Mobility Model that enable attribution based on the marginal carbon intensity of electricity instead of the weighted average, depending on the type of analysis to be carried out.

Correcting the carbon intensity of electricity to account for the effect of power trade requires collecting data at trading partner level. The quality of the correction depends on the quality of the data reported by the trading partners, which are not available for all countries. Possible improvements include enhancing the data quality of the correction of carbon intensity based on electricity trade and carrying out such corrections for non-OECD countries.

Hydrogen

Data

The data used to calculate the hydrogen pathway well-to-tank emissions come from a variety of sources. Where available, IEA modelling – including data from both the World Energy Outlook division (on natural gas and oil products' upstream emissions) and ETP supply modelling – is used to maintain internal consistency. The ETP supply model provides assumptions on hydrogen production efficiency (feedstock and other inputs) and direct emissions for each hydrogen pathway.

Upstream emissions related to the production, processing and transport of biomass and coal feedstocks are not covered by IEA modelling and instead are taken from the GREET model. For downstream stages, such as diesel consumption for truck transport of hydrogen and electricity consumption for hydrogen liquefaction, compression and dispensing, GREET energy intensities are incorporated into the analysis. The methods used to estimate the emissions intensities of these energy inputs are described above.

Methodology

Regional and temporal variability in fuel input and feedstock emissions factors from other aspects of this analysis are used to estimate hydrogen well-to-tank emissions. For example, the natural gas emissions factors based on World Energy Outlook data are used in the steam methane reforming pathways. Similarly, grid electricity emissions factors are used for the electrolytic hydrogen pathway as well as other for other processes in the hydrogen supply chain (e.g. for compression energy inputs for pipeline transport and station dispensing).

The quantity of energy feedstock required for hydrogen production (i.e. hydrogen production efficiency) is taken from the IEA ETP supply model. The same model results are used for the emissions from production processes, including assumptions on the efficiency of carbon capture technologies for the relevant pathways. For the biomass gasification pathway, biogenic CO_2 is balanced in the well-to-tank phase, or treated as negative when CCUS is applied, as described in the section below on biogenic CO_2 accounting. Inputs from GREET considering the use of poplar biomass are used as representative for this pathway.

Default assumptions on transport mode, distance and energy intensity from GREET are used to estimate hydrogen transport emissions. Gaseous hydrogen is thus assumed to be delivered to stations via pipeline and liquid hydrogen is assumed to be transported by a mix of rail, barge and liquid tanker. For renewable pathways (i.e. biomass gasification with and without CCUS and renewable electrolysis), it is assumed that renewable electricity is also used to power the liquefaction process.

For the Stated Policies Scenario and Announced Pledges Scenario, the IEA supply model results are used to determine the share of overall hydrogen production from each pathway by region and year, which are then used to calculate the weighted average emissions of hydrogen being consumed in the given region and year.

Limitations and future improvements

For simplicity, woody biomass, specifically poplar, was selected as the representative feedstock in the biomass gasification pathway. Improvements to this methodology include expanding the feedstock options analysed and varying the process efficiencies (including cultivation) and fuel input carbon intensities by region and year. Similarly, the upstream emissions factor for coal is taken from GREET and should be adjusted to account for regional and temporal variability in coal types and mining techniques.

Currently, hydrogen distribution is based on GREET default assumptions. Even without data on current and expected distribution modes and distances, the modelling could be improved by refining modal choice assumptions based on average station sizes and regional demand over time. Further, as with the other pathways, fuel switching within transport modes is not accounted for.

Additional hydrogen pathways could be added, such as by-product hydrogen from industrial processes (e.g. chlor-alkali process) or more innovative production technologies such as solar thermochemical processes.

Synthetic fuels

Data

As with the hydrogen pathways, a mix of data sources is used to estimate synthetic fuel well-to-tank emissions. The ETP supply model provides data on the hydrogen, electricity and CO_2 inputs for six synthetic fuel production pathways. Upstream emissions associated with hydrogen and electricity supply chains are described in previous sections of this annex. The electricity requirements for carbon capture from concentrated sources (fossil and biomass-based plants) are taken from GREET. The electricity requirement for direct air capture is from the ETP supply model. Default assumptions in GREET are used to calculate emissions associated with synthetic fuel transmission, distribution and dispensing.

Methodology

A power-to-liquids process is assumed for the production of synthetic diesel. It is assumed that both CO_2 and hydrogen are produced onsite, meaning that emissions incurred in the delivery of these inputs are not considered. For the three pathways with hydrogen production from renewable electrolysis, it is assumed that renewable electricity is also used for the power-to-liquids process, including for carbon capture in the case of direct air capture. Both the capture of biogenic CO_2 and direct air capture are considered to result in negative well-to-tank emissions, which are later balanced by the combustion of synthetic fuels in the tank-to-wheel phase.

Limitations and future improvements

Especially for non-direct air capture pathways, the transport of CO_2 to the synfuels plant should be incorporated in the well-to-tank analysis.

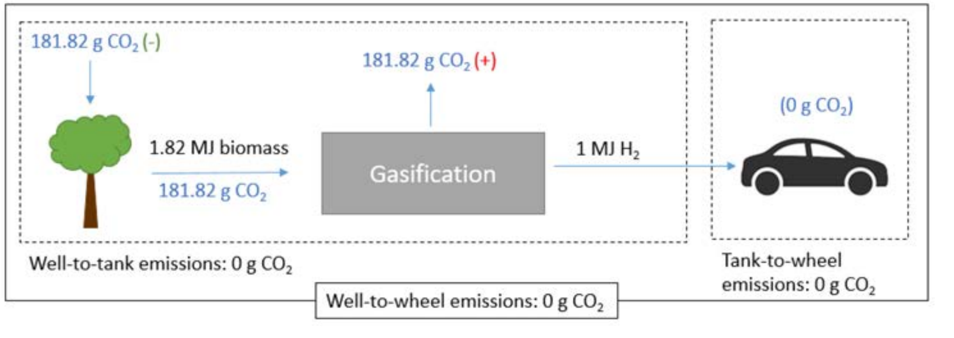
Biogenic CO_2 accounting

The growth of biomass involves the uptake of atmospheric CO_2 in the biomass. In many life-cycle assessment studies, it is assumed that the biogenic carbon emissions from the combustion of biomass are equivalent to the amount of CO_2 previously sequestered during the growth of the biomass, though this balanced accounting is dependent on the timescale considered. In addition to the temporality of emissions, a complete assessment should consider changes in the soil carbon content, as well as the net balance of sequestration and emissions of other greenhouse gases (e.g. nitrogen fixation and soil emissions of nitrogen oxides) and biogeochemical processes that occur between the soil, plant and atmosphere. Here, as in many life-cycle assessment studies, we assume the sustainable production of biomass with no changes to the soil carbon content, and thus a balance between the carbon uptake in biomass and the biogenic carbon emissions from combustion.

Some methods of accounting for biogenic CO_2 emissions, such as that applied in the JEC Well-to-Wheels (v5) analysis, do not explicitly include a crediting for CO_2 uptake during feedstock growth or the release of biogenic CO_2, since it is assumed they are exactly balanced. For our well-to-wheel accounting (Chapter 4), we choose to show both the credit for CO_2 uptake in the well-to-tank phase, as well as the CO_2 release in both the fuel processing (well-to-tank) and the fuel combustion (tank-to-wheel) phases. This method enables a differentiation in the tank-to-wheel phase between biofuels (and synthetic fuels produced from biogenic CO_2) and the potentially "zero-emissions" (process emissions) fuels such as hydrogen and electricity.

In the case of biogenic carbon flows for the production of hydrogen via biomass gasification, the emissions from biomass gasification process (shown with a red plus sign in figure below) are assumed equivalent to the CO_2 uptake during biomass growth (shown with a negative sign). Thus, the well-to-tank emissions (again, considering only the biogenic CO_2) add up to zero. Fuel cell electric vehicles are "zero-emission" vehicles – their operation emits no CO_2 at the tailpipe, meaning that the well-to-wheel biogenic emissions are also zero.

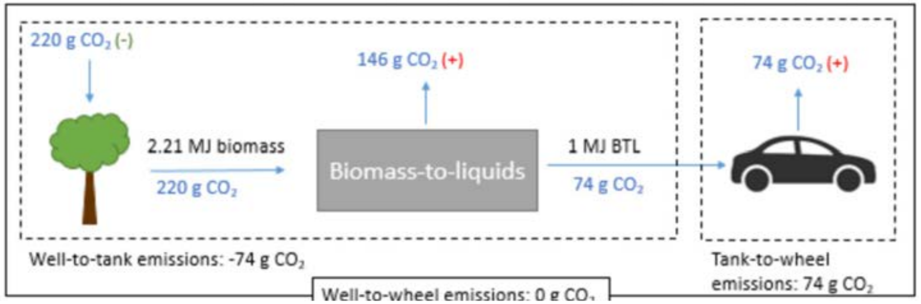
Biogenic carbon accounting for hydrogen from biomass gasification pathway



Note: H_2 = hydrogen.

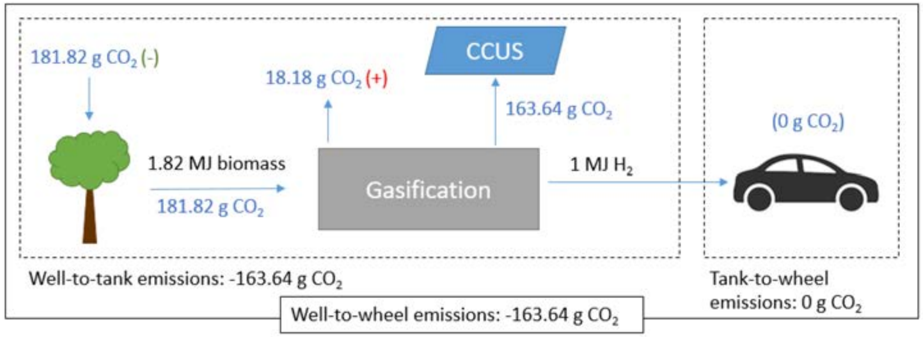
Biofuels, on the other hand, do produce CO_2 emissions when combusted in the tank-to-wheel phase. With biomass-to-liquids fuel pathway, the tank-to-wheel phase results in the release of biogenic emissions (indicated with a red plus sign in figure below). The biomass-to-liquids process also results in positive emissions, in the well-to-tank phase, though this is more than offset by the negative emissions credited to the growth of the biomass feedstock. The well-to-wheel emissions add up to zero in the accounting of biogenic CO_2.

Biogenic carbon accounting for biomass-to-liquids pathway

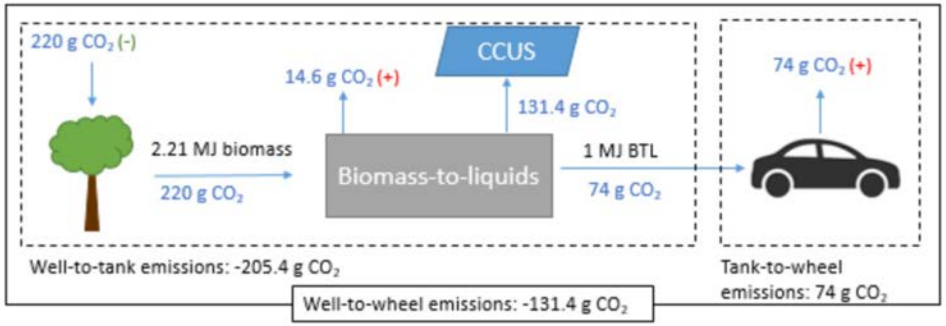


When carbon capture technologies are used to sequester the CO_2 emissions of fuel processing, the result is a net withdrawal of CO_2 emissions from the atmosphere. Thus, the well-to-wheel emissions are equivalent to the amount of biogenic CO_2 captured by the CCUS technologies, which is assumed to be 90% of the biogenic emissions from fuel processing. The two figures below illustrate the biogenic carbon flows of hydrogen and biomass-to-liquids production with CCUS.

Biogenic carbon accounting for hydrogen from biomass gasification with CCUS pathway

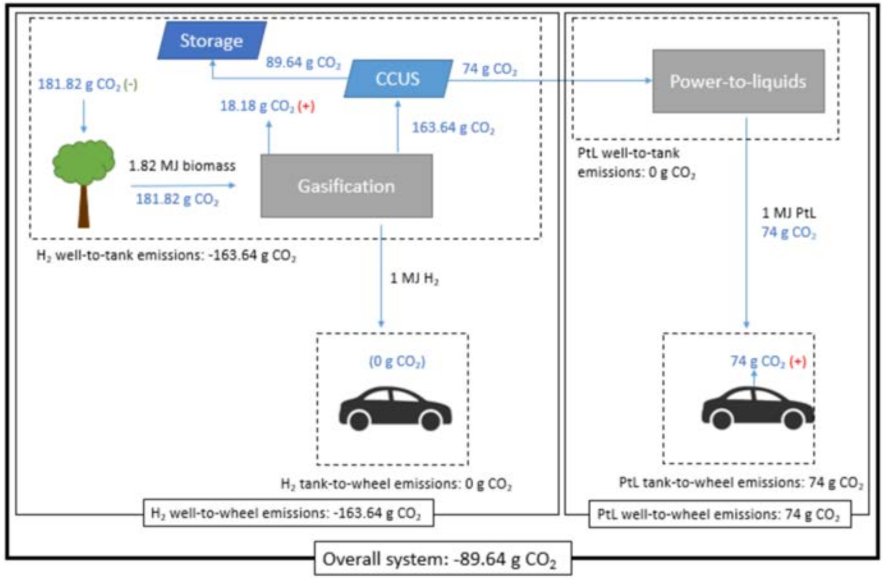


Biogenic carbon accounting for biomass-to-liquids with CCUS pathway



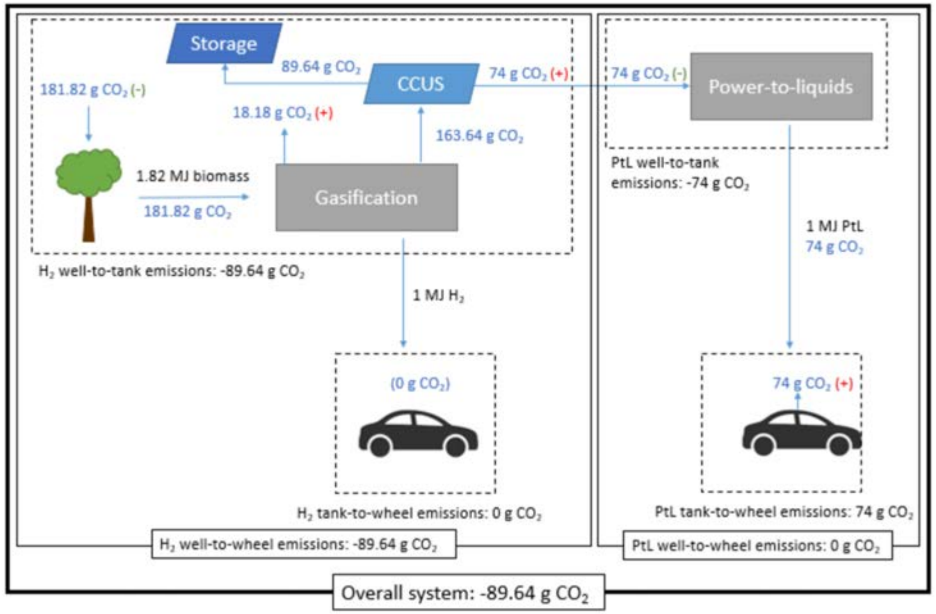
This accounting is valid only when the captured CO_2 is stored permanently (or at least beyond the timescale of the analysis period). When some portion of the captured CO_2 is utilised, and emitted, this accounting must be adjusted. For example, when biogenic CO_2 is used for the production of synthetic fuels (or "e-fuels"), the CO_2 contained in the synthetic fuel is released during the combustion of the fuel. The figure below illustrates the flow of biogenic CO_2 considering hydrogen production from biomass gasification with CCUS and power-to-liquids production using a portion of the captured CO_2. The well-to-tank emissions for the hydrogen pathway remain unchanged, and at the overall system level, including the hydrogen and power-to-liquids fuel pathways, biogenic emissions are equivalent to the (negative) emissions that are stored. This accounting gives the hydrogen pathway full credit for the emissions uptake in producing the biomass, and none of this credit is given to the power-to-liquids pathway.

Biogenic carbon accounting where carbon captured from hydrogen production via biomass gasification is supplied to power-to-liquids fuel production



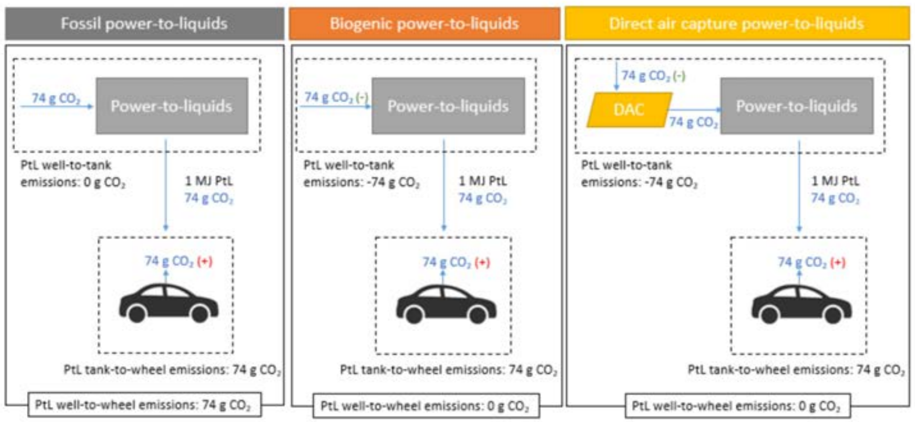
We can choose to allocate a portion of the credit of CO_2 uptake to the power-to-liquids pathway, however. This is done by counting the CO_2 that is utilised for synfuels as a positive in the hydrogen well-to-tank phase and negative in the power-to-liquids well-to-tank phase. This accounting, of course, does not change the overall system emissions, but serves to credit the power-to-liquids pathway with its use of biogenic CO_2. The well-to-wheel emissions for synthetic fuels produced with biogenic CO_2 add up to zero, and the well-to-wheel emissions for the hydrogen pathway are equivalent to the (negative) CO_2 emissions that are stored.

Applied method of biogenic carbon accounting where carbon captured from hydrogen production via biomass gasification is supplied to power-to-liquids fuel production



This method of accounting means that the well-to-wheel emissions from power-to-liquids with CO_2 from biogenic sources and from direct air capture will be the same. This is reasonable since, considering a long enough time frame, the biomass growth is equivalent to direct air capture in terms of sequestering atmospheric CO_2. On the other hand, we consider the analytical period sufficiently short that the CO_2 from fossil sources does not get credited with sequestering CO_2 from the atmosphere. Thus, the well-to-wheel emissions for power-to-liquids with CO_2 from fossil sources results in positive emissions equal to those resulting from fuel combustion.

Accounting method for CO_2 inputs across power-to-liquids pathways



Note: DAC = direct air capture.

Tank-to-wheel emissions

Currently, tank-to-wheel emissions include only the CO_2 emitted when gasoline, diesel and methane blends (from both fossil and biogenic pathways) are combusted in internal combustion engine vehicles. A high priority in updating the analysis here will be to add to the IEA Mobility Model estimates of emissions incurred from the following processes:

- **criteria air pollutants** that are also greenhouse gases (black carbon, methane, nitrous oxide)
- **hydrofluorocarbons and chlorofluorocarbons** used in mobile air conditioning in light-duty vehicles
- **methane slip** in compressed and liquefied natural gas internal combustion engine vehicles
- **nitrous oxide emissions** resulting from degraded or defective selective catalytic reduction after-treatment systems
- **evaporative emissions** from the fuel tank that occur even when the vehicle is not driven, relevant for all internal combustion engine vehicles as well as for fuel cell electric vehicles.

Abbreviations and acronyms

AFC TCP	Advanced Fuel Cells Technology Collaboration Programme
AMF TCP	Advanced Motor Fuels Technology Collaboration Programme4
AMT	Advanced Materials for Transportation
APS	Announced Pledges Scenario
BEV	battery electric vehicle
bio-FT	biomass gasification and Fischer-Tropsch synthesis
bio-SNG	bio-synthetic natural gas
CAFC	corporate average fuel consumption
CAFE	corporate average fuel economy
CCGT	combined cycle gas turbine
CCUS	carbon, capture, utilisation and storage
CNG	compressed natural gas
CO_2	carbon dioxide
EPA	Environmental Protection Agency
FAME	fatty acid methyl esters
FCEV	fuel cell electric vehicle
GFEI	Global Fuel Economy Initiative
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HEFA	hydroprocessed esters and fatty acids
HEV	hybrid electric vehicle
HEV TCP	Clean and Efficient Combustion, Hybrid and Electric Vehicles Technology Collaboration Programme
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCV	light commercial vehicle
LNG	liquefied natural gas
LPG	liquefied petroleum gas
NEDC	New European Driving Cycle
NZE	Net Zero by 2050 Scenario
OICA	International Organisation of Motor Vehicle Manufacturers (Organisation Internationale des Constructeurs d'Automobiles)
PHEV	plug-in electric vehicle
SAFE	Safer Affordable Fuel Efficient
STEPS	Stated Policies Scenario
SUV	sport utility vehicle
TCP	Technology Collaboration Programme
WLTC	Worldwide Harmonized Light-Duty Vehicle Test Cycle

Units of measure

cm^3	cubic centimetre
g CO_2-eq	gramme of carbon dioxide equivalent
Gt	gigatonne
kg	kilogramme
km	kilometre
kW	kilowatt
kWh	kilowatt-hour
L	litre
Lge	litre of gasoline equivalent
m^2	metre squared
MJ	megajoule

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