TEXTE
14/2024

Final report

Analysis of the environmental impacts of vehicles with alternative drivetrains or fuels on the way to greenhouse gas-neutral transport

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Abstract: Analysis of the environmental impacts of vehicles with different drivetrain and fuel options in Germany during the transition towards a greenhouse gas neutral mobility

In order to achieve Germany's medium- and long-term climate protection targets in the transport sector in addition to traffic avoidance and modal shift, the use of alternative powertrains and alternative fuels is necessary. Based on the average vehicles, powertrains and fuels available today, a plausible development is examined that includes both vehicle characteristics and the increasing share of synthetic (electricity-based) fuels. The end point is a largely decarbonized world in 2050. Average passenger cars, light commercial vehicles and trucks for the model years 2020, 2030 and 2050 are examined. The environmental impact per kilometre driven is calculated using a comprehensive Life Cycle Assessment (LCA) that includes vehicle production, use, maintenance and disposal, as well as the provision of synthetic, biogenic and fossil fuels and electricity. Overall, for all vehicle types and model years, the battery electric vehicle concepts are the superior solution in terms of greenhouse gas emissions and cumulative energy consumption. In the medium term, however, their use of the German electricity mix leads to significant negative effects in terms of other relevant environmental impacts. In a decarbonized world, all technologies are at a low level in terms of environmental impact, but most environmental impacts do not decrease as much as global warming potential. While GHG emissions per vehicle kilometre for passenger cars are reduced by an average of 96% compared to 2020, acidification and particulate matter, for example, are reduced by only 40-60%. Through sensitivity analyses, the study also identifies key levers for short- and long-term improvements. These relate mainly to the raw materials used in vehicle production and electricity generation, including synthetic fuels.

Kurzbeschreibung: Analysis of the environmental impacts of vehicles with alternative drivetrains or fuels on the way to greenhouse gas-neutral transport

Um die mittel- und langfristigen Klimaschutzziele Deutschlands im Verkehrssektor zu erreichen, ist neben der Verkehrsvermeidung und Verlagerung auch der Einsatz von alternativen Antrieben und alternativen Kraftstoffen notwendig. Ausgehend von heute verfügbaren durchschnittlichen Fahrzeugen, Antrieben und Kraftstoffen wird eine plausible Entwicklung untersucht, die sowohl die Fahrzeugeigenschaften als auch die steigende Beimischung synthetischer, strombasierter Kraftstoffe umfasst. Endpunkt ist eine weitestmöglich defossilisierte Welt im Jahr 2050. Untersucht wird jeweils durchschnittliche Pkw, leichte Nutzfahrzeuge und Lkw der Baujahre 2020, 2030 und 2050. Die Umweltwirkungen je gefahrenem Kilometer werden durch eine umfassende ökobilanzielle Analyse ermittelt, welche sowohl die Fahrzeugherstellung, -nutzung, -wartung und -entsorgung umfasst, als auch die Bereitstellung von synthetischen, biogenen und fossilen Kraftstoffen und Fahrstrom. Insgesamt zeigen sich die batterieelektrischen Fahrzeugkonzepte für alle Fahrzeugtypen und Baujahre als überlegene Lösung bezüglich der Treibhauswirkung und des kumulierten Energieaufwandes. Mittelfristig ist für sie die Nutzung des deutschen Strommixes aber noch mit deutlichen negativen Wirkungen bei anderen relevanten Umweltwirkungen verbunden. In einer defossilisierten Welt liegen alle Technologien auf niedrigerem Niveau bezüglich ihrer Umweltbelastung, doch die meisten Umweltwirkungen gehen nicht so stark zurück wie das Treibhauspotenzial. Während dieses je Fahrzeugkilometer bei den Pkw durchschnittlich um 96 % gegenüber 2020 sinkt, verringern sich etwa Versauerung und Feinstaubbelastung nur um 40-60 %. Auch durch ihre Sensitivitätsanalysen zeigt diese Studie zentrale Stellschrauben zu kurz- und langfristigen Verbesserungen. Diese betreffen vor allem die Rohstoffe zur Herstellung der Fahrzeuge und die Erzeugung des Stroms – auch für synthetische Kraftstoffe.

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List of abbreviations

AEL	Alkaline electrolysis
AP	Acidification Potential
BEV	Battery-electric vehicle
BMS	Battery management system
BtL	Biomass to Liquid (Production of liquid fuel from biomass)
CFC-11eq	Chlorofluorocarbon-11 equivalents
CNG	Compressed Natural Gas
CSP	Concentrating Solar Power
DAC	Direct Air Capture (CO_2 capture from the air)
EP_aq	Eutrophication Potential (aquatic)
EP_ter	Eutrophication Potential (terrestrial)
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch (Synthesis)
GL	GreenLate Scenario
GS	GreenSupreme Scenario
GWP	Global Warming Potential
H_2	Hydrogen
H2-ICE	Hydrogen Internal Combustion Engine
HBEFA	Handbook of Emission Factors for Road Transport
HDT	Heavy-Duty Trucks
ICE	Internal Combustion Engine
KBA	Federal Motor Transport Authority
CED	Cumulative Energy Demand
CRD	Cumulative Raw Material demand
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFP	Lithium Iron Phosphate
LHV	Lower Heating Value
Li	Lithium
LCV	Light Commercial Vehicles
LNG	Liquefied Natural Gas
NEDC	New European Driving Cycle
NZL	New Registrations
MeOH	Methanol
MtG	Methanol-to-Gasoline
NCA	Nickel Cobalt Aluminium Oxide

NMC	Nickel Manganese Cobalt Oxide
O-BEV	Overhead Catenary Battery Electric Truck
O-HEV	Overhead Catenary Hybrid Electric Truck
ODP	Ozone Depletion Potential
PBtL	Power and Biomass to Liquid (Production of liquid fuel with electricity and biomass)
PEMEL	Polymer electrolyte membrane electrolysis
PHEV	Plug-in hybrid vehicle
PGM	Platinum group metals
PM2.5	Particulate matter formation (<2.5 µm)
POCP	Photochemical Ozone Creation Potential
PtG	Power to Gas (Production of gaseous fuel with electricity)
PtL	Power to Liquid (Production of liquid fuel with electricity)
PV	Photovoltaics
R-10	Carbon tetrachloride (coolant)
R-116	Hexafluoroethane (coolant)
SMR	Steam Methane Reforming
S-CNG	Synthetic Compressed Natural Gas
S-LNG	Synthetic Liquefied Natural Gas
SNS	Synthetic Natural Gas
SUV	Sport Utility Vehicle
TFE	Tetrafluoroethylene
WindOff	Wind energy at sea (offshore)
WindOn	Wind energy on land (onshore)
WEA	Wind turbine
WTT	Well-to-Tank
WTW	Well-to-Wheels
YOM	Year of Manufacture
zGG	Permissible total weight

1 Introduction

In order to achieve Germany's medium- and long-term climate protection goals in the transport sector, measures are needed at all levels. In addition to the overarching strategies of avoiding traffic and shifting traffic to climate-friendly modes of transport, the use of alternative powertrains and fuels is necessary to achieve the goal of a greenhouse gas-neutral transport system by 2050. To achieve this, different combinations of powertrains and fuels are under discussion.

As the powertrain and fuel combinations under consideration affect all aspects of a vehicle's life cycle - from the production of the vehicle itself, through its use and maintenance, to its energy supply - a comprehensive LCA approach is chosen that takes all these aspects into account. This is the only way to identify possible shifts of environmental impacts to other regions or stages of the life cycle. It also highlights the potential advantages and disadvantages of options in different environmental impact categories and helps to address conflicting environmental objectives. Due to the different levels of technological maturity and the dynamic development, the current development status of the vehicles and the energy system is considered as well as the possible development in the medium (2030) and long term (2050).

2 Methodology

2.1 Goal and scope

In recent years, the market uptake of electric vehicles has gained momentum, especially in the passenger car sector. Furthermore, due to the greenhouse gas quota for fuels and the stringent CO_2 fleet targets for passenger cars and light commercial vehicles (EU Regulation 2019/631), as well as the introduction of fleet targets for heavy duty vehicles from 2025 onwards (EU Regulation 2019/1242), the share of vehicles with alternative powertrains or fuel types will increase in all vehicle sectors.

Therefore, this study covers not only passenger cars, but also light commercial vehicles (LCVs) as well as heavy-duty vehicles (HDVs). Conventional petrol and diesel engines can run on either fossil or synthetic fuels as well as gaseous fuels such as CNG or LNG. Hydrogen can also be used in an internal combustion engine. In addition, electric vehicles allow the direct use of electricity (stored in a traction battery or directly from the overhead line) and fuel cells allow the conversion of hydrogen into electricity. Finally, plug-in hybrids allow the combination of direct electricity use with different fuels by combining electric and internal combustion engine.

All powertrain-vehicle combinations in Table 1 are examined for each of the model years shown. We assume that alternative propulsion systems for heavy-duty vehicles will not be available on a larger scale before 2030.

Table 1: Powertrain-vehicle combinations investigated

Vehicle	Powertrain	2020	2030	2050
Compact class passenger car/ LCV N1-III	Petrol	X	X	X
	Diesel	X	X	X
	CNG	X	X	X
	PHEV-Petrol	X	X	X
	BEV	X	X	X
	FCEV	X	X	X
Heavy-duty trucks 40t	Diesel	X	X	X
	Dual-fuel LNG	X	X	X
	LNG (CI)	X	X	X
	H2-ICE		X	X
	FCEV		X	X
	BEV		X	X
	O-HEV*		X	X
	O-BEV**		X	X

* O-HEV: Overhead catenary hybrid electric truck

** O-BEV: Overhead catenary battery electric truck

A Life Cycle Assessment (LCA) methodology based on ISO standards 14040 and 14044 is used as the method to comprehensively analyse the environmental and resource impacts over the entire life cycle. Production, maintenance and disposal of the vehicles, the direct emissions from vehicle operation and the environmental impact of the energy sources used (fuel and electricity, including charging and refuelling infrastructure) are considered. The road infrastructure is not included, as it does not differ between the different powertrain concepts.

The environmental impacts of fuel and electricity supply prior to use in the vehicle play an important role. These impacts occur along the entire production chain, from the extraction of raw materials, the production of electricity and the synthesis of gaseous or liquid fuels, through storage and transport to the market, to conditioning at the filling or charging station. The benchmark for alternative fuels is today's production based on fossil fuels: diesel and petrol from crude oil, CNG and LNG from natural gas, and hydrogen from steam reforming of natural gas. The current blending of biofuels is also included.

For the medium- and long-term development, the production of synthetic fuels based on renewable electricity is investigated. The basic technological assumptions are largely in line with those of the preceding UBA project SYSEET (Liebich et al. 2020). For all electricity-based fuels (PtL, PtG and PBtL) photovoltaics, onshore and offshore wind power as well as concentrating solar power (CSP) are considered as renewable electricity sources. Furthermore, the production of synthetic fuels with the German grid electricity mix is examined and used for all vehicles manufactured in 2050. Electric vehicles are operated with the German grid electricity mix in all reference years. Carbon for the synthesis of hydrocarbons is captured as CO_2 from the air. Hydrogen is produced in alkaline electrolyzers (AEL). Synthetic diesel and petrol are produced in plants based either on a Fischer-Tropsch synthesis or on the Methanol-to-Gasoline (MtG) process. Synthetic natural gas (SNG) is produced using the Sabatier process.

Domestic production in Germany and the production in Morocco are examined as examples of production locations, and possible import routes (pipeline, tanker) and distribution in Germany are investigated. Table 2 shows the list of process steps considered in this study for the provision of synthetic fuels.

Table 2 : Process steps and their variations for the provision of synthetic fuels

Fuel	Electricity	Locations	Electrolysis	CO_2	Synthesis	Transport
Petrol Diesel CNG LNG	WindOn WindOff PV CSP	Germany Morocco	AEL	DAC (air)	PtL (FT, MtG) PtG (SNG, electrolysis)	Ship (PtL) Pipeline, gas grid (PtG) Truck (PtL)

CNG: Compressed Natural Gas, LNG: Liquefied Natural Gas,
PV: Photovoltaics, WindOff: Offshore wind energy, WindOn: Onshore wind energy,
AEL: Alkaline Electrolysis, DAC: Direct Air Capture, PtL: Power to Liquid, PtG: Power to Gas.

2.2 Life cycle assessment

The methodology in this study follows the international standards for life cycle assessment ISO 14040 and ISO 14044 (but without an external critical review). The analysis considers the complete life cycle of the selected fuel-powertrain-vehicle combinations, from raw material extraction to processing, use and disposal. While we have modelled the foreground system ourselves (including full load hours, lifetimes, vehicle compositions etc.), we have taken the associated individual processes or modules for the background system from the ecoinvent database. Specific technology parameters (e.g., construction of wind and PV electricity generation plants) were also updated in the background system. The resulting models are used to calculate the resource requirements and relevant impact indicators.

For the life cycle impact assessment, the following categories are evaluated:

- Climate change: Global warming potential (GWP) over a period of 100 years according to (IPCC 2014) in kg CO_2eq.
- Acidification: Acidification Potential (AP) according to (Hauschild und Wenzel 1998) in g SO_2eq.
- Eutrophication (aquatic): Eutrophication potential, nutrient components entering the water (EP_aq) according to (Heijungs et al. 1992)in g PO_4eq.
- Eutrophication (terrestrial): Eutrophication potential, nutrient fractions (EP_ter) deposited on land according to (Heijungs et al. 1992) in g PO_4eq.
- Photochemical ozone creation (summer smog): Tropospheric ozone creation potential (POCP) according to ReCiPe (Goedkoop et al. 2009) in g C_2H_4eq.
- Ozone Depletion Potential (ODP): Potential to deplete the stratospheric ozone layer, according to (WMO 2014) in g CFC-11eq.
- Particulate matter formation: Harmful effect on human health caused by particles <2.5 µm (PM2.5) according to (De Leeuw 2002; WHO 2006) in kg PM2.5eq .
- Cumulative energy demand (CED): Energy used in MJ (LHV)
- Cumulative raw material demand (CRD): Resource use in kg
- Hemeroby: Land use according to (Fehrenbach et al. 2015) in m^2a
- Freshwater demand: Fresh water intake in l H_2O (without cooling water and input from hydropower plants)

During the evaluation of the LCIA results, a normalisation is carried out which helps comparing the benefits and additional burdens of the analysed systems in different impact categories. The normalisation step is an optional part of the Life Cycle Assessment according to ISO 14044 (ISO 2006). It relates the environmental impacts of the process under consideration in a specific impact category to the total impact in a defined region during a reference year, e.g. the acidification caused by the use of a car per vehicle kilometre to the total anthropogenic acidification in Germany in the year 2000. If the annual impact per inhabitant is used as a reference instead of the total impact, this is referred to as the average impact per capita. Normalisation allows to distinguish between significant and insignificant results. For example, if one type of powertrain generates several times the impact of another type of powertrain in a given impact category, this is only significant if the contribution to the per capita impact is also high. Table 3 shows the population averages used to normalise the impact results for Germany in 2020.

Table 3 : Average per capita environmental burdens in Germany 2020

Impact category	Unit	EDW	Sources ifeu calculations are based on:
GWP	t CO_2eq	9,0	(Günther et al. 2023)
AP	kg SO_2eq	25	(Griffke 2023)
EP_ter	kg PO_4 eq	3,9	(Griffke 2023)
EP_aq	kg PO_4 eq	3,2	(Umweltbundesamt 2020)
POCP	kg ethylene	13	(Griffke 2023)
ODP	kg CFC11 eq	0,022	(Günther et al. 2023)
PM2.5	kg PM2.5 eq	18	(Griffke 2023)
CRD	t	50	(Destatis 2021; Giegrich et al. 2012)
CED	GJ	145	(Buttermann et al. 2023)
Freshwater demand	m^3	91	(DESTATIS 2022, 2023)
Hemeroby	m^2a	$1,4*10^3$	(Fehrenbach et al. 2019)

2.3 Scenarios

Scenarios are often used to show how a specific goal like a GHG-neutral society can be achieved and what the resulting transformation might look like. In the RESCUE project, the Federal Environment Agency investigated the links between climate protection and resource use. Six scenarios were developed to find solutions for significantly reducing resource use and greenhouse gas emissions in Germany in the future (Purr et al. 2019). The scenarios describe changes in all areas of society - from industry, trade and services to buildings, mobility, electricity, and heat supply. All RESCUE scenarios achieve greenhouse gas neutrality in 2050 (i.e., a reduction of greenhouse gas emissions of at least -95 % compared to 1990). The scenarios differ in terms of the transformation speed and the technologies used. The assumptions on societal changes also differ.

In the context of ifeu's work on prospective life cycle assessment for this study, two RESCUE scenarios were used in particular:

- The **GreenSupreme** scenario assumes a large number of technical innovations, integration of efficient sector coupling technologies and the rigorous exploitation of energy efficiency potentials. The ambition to reduce greenhouse gases and to increase energy and material efficiency is at a very high level.
- The transformation in the **GreenLate** scenario also leads to GHG-neutrality. The initial level of ambition is much lower, though. The necessary measures and investments are therefore deployed later and during a shorter period - at the end of the first half of the century. The lower level of societal understanding for the measures needed to increase material and energy efficiency leads to a reduced pressure to innovate. Raw material efficiency and recycling potentials are only partially exploited.

Assumptions were taken from these two scenarios to model the development of the fuel supply and the electricity mixes. Furthermore, important technological changes were modelled to adjust the background system. With the increasing decarbonisation of the energy system and all industrial processes, the importance of the foreground processes (e.g. use emissions of vehicles) decreases and the background processes (e.g. production of wind power and PV plants) increases. To determine the potential environmental impacts of future raw materials and energy sources, we modelled an LCA background system according to the GreenSupreme scenario. The calculation was largely carried out in the UBA project REFINE (Dittrich et al. in progress) based on the ecoinvent life cycle assessment database. For this purpose, the ecoinvent cut-off database version 3.7.1 (from December 2020) was used and adapted to the reference years 2030, 2040 and 2050. This elaborate development builds on the preparatory work in the UBA project SYSEET (Liebich et al. 2020) and was realised together with the partner ecoinvent, a Swiss-based non-profit organisation.

2.4 Standard cases

The models used allow the calculation of many combinations and variations of vehicles and fuels. To derive key results, standard cases were defined that represent a plausible development in vehicle and battery technology, fuel efficiency, and in the background system.

The results per vehicle kilometre are mainly influenced by the following factors:

- Vehicle characteristics and energy consumption
- Developments in vehicle and battery production
- Environmental impacts of the energy sources used (including combustion emissions and the use of renewable electricity for vehicle operation)
- Changes in the background system due to progressive decarbonisation

The assumptions regarding these influencing factors and the derived standard cases are described below.

Developments in vehicle energy consumption and characteristics

Key factors influencing the environmental performance of vehicles are the vehicle characteristic and the resulting energy consumption.

For passenger cars, a medium-sized average compact class car is considered based on the newly registered cars in Germany in 2020. The most important vehicle characteristics and consumption trends are briefly summarised here. In principle, the diesel engine has efficiency advantages over the petrol engine, but the typical diesel compact car in Germany today is heavier than the typical petrol compact car. This leads to very similar consumption figures in MJ per kilometre for the two vehicle concepts. In contrast, the typical CNG compact car is slightly more efficient, as relatively fuel-efficient cars were newly registered in 2020. For petrol/diesel/CNG cars, efficiency improvements of 2.1% per year until 2025 and 1.4% per year between 2025 and 2030 are assumed. Thereafter, fuel consumption remains constant. For passenger cars with alternative propulsion systems, consumption is assumed to remain constant, as it can be expected that any efficiency improvements will be offset by a less favourable usage profile. In addition, the vehicle weights of electric cars remain almost constant, as it is assumed that batteries will become lighter per kWh of capacity, but that driving ranges (and therefore battery sizes) will increase at the same time.

For heavy-duty vehicles a tractor-trailer with a gross maximum weight of 40 t is assessed. As there were very few models with an alternative powertrain on the market in 2020, electric or hydrogen trucks are analysed from the year 2030 onwards. In addition to diesel trucks, duel-fuel LNG or LNG-trucks are covered. Today's dual-fuel LNG trucks have a diesel engine and therefore a similar efficiency as diesel trucks. In addition to LNG, they use diesel fuel for ignition, leading to an average diesel share of around 40%. Pure LNG trucks have a spark-ignition engine and therefore a 24% higher energy consumption compared to diesel trucks. For heavy-duty trucks with conventional powertrains, efficiency improvements of 0.5% per year are assumed until 2030. After that, consumption remains constant. In the case of vehicles with alternative powertrains, the 15% increase in fuel consumption of the H2-ICE vehicle compared to the FCEV is particularly noteworthy and may offset the benefits of eliminating the fuel cell.

An important factor influencing both vehicle energy consumption and vehicle production is the size of the battery in electric vehicles. The range (and therefore the size of the traction battery) of all alternative powertrain vehicles increases over the years, as shown in Table 4.

Table 4 Assumed development of the ranges and usable battery sizes of electric vehicles

	Battery size 2020	Real range 2020 (electric)	Battery size 2030 - 2050	Real range 2030 - 2050 (electric)
Car BEV	55 kWh	300 km	80 kWh	440 km
Car PHEV	10 kWh	53 km	14 kWh	75 km
LCV BEV	55 kWh	150 km	75 kWh	200 km
LCV PHEV	14 kWh	40 km	18 kWh	55 km
HDV BEV	-	-	730 kWh	500 km
HDV O-BEV	-	-	160 kWh	120 km (w/o overhead line)

Developments in vehicle and battery technologies

Furthermore, improvements in the vehicle manufacturing phase (mainly due to technological advances in traction batteries and fuel cells) are also included. A brief overview of the technological developments and improvements in the background system are given in Table 5. In the year 2050, it is assumed that vehicle and battery production is completely decarbonised, no longer using any fossil-fuel based processes or materials.

Table 5: Technology level and background system of vehicle and battery production

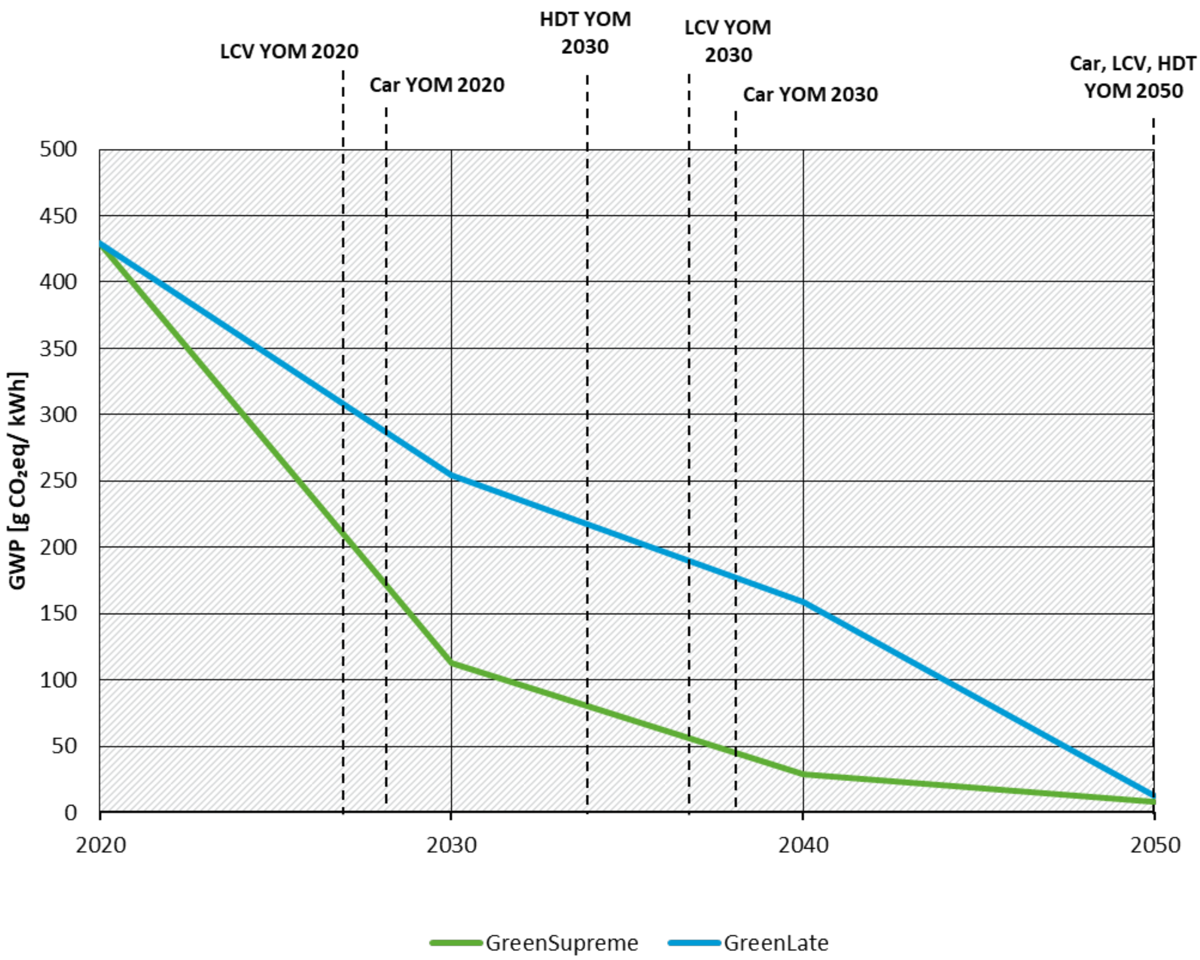
Year of manufacture	Background system	Battery technology	Fuel cell
2020	Today	NMC622 (with 150 Wh/kg at system level)	PEMFC 2020 (with 380 mg platinum loading per kW)
2030	Today	NMC811 (with 200 Wh/kg at system level)	PEMFC 2030+ (with 165 mg platinum loading per kW)
2050	GreenSupreme 2050	Li-Air (with 1500 Wh/kg at system level)	PEMFC 2030+ (with 165 mg platinum loading per kW)

Electricity and fuel mixes

Key assumptions are also made for the use of electricity and the production of synthetic fuels. German grid electricity mixes are used as the traction energy for battery electric and hybrid electric vehicles. In 2050 German grid electricity (which is fully renewable at that time) is also used for the production of electricity-based fuels according to the GreenSupreme scenario.

Figure 1 shows the global warming potential of the German grid electricity mixes according to the GreenSupreme and GreenLate scenarios.

Figure 1: Global warming potentials per kWh of the German grid electricity mixes according to the GreenSupreme and GreenLate scenarios



Source: own calculations ifeu

Starting point is the global warming potential of the German electricity mix in 2020. The different scenarios assume different rates of decarbonisation in the electricity sector and in the background system relevant to the energy infrastructure. Accordingly, the global warming potential per kilowatt-hour decreases at different rates. Battery and hybrid electric vehicles use grid electricity with different global warming potentials as propulsion energy during their lifetime. In Figure 1, the dashed lines represent the average electricity mix for a given year of vehicle manufacture. For example, a passenger car produced in 2020 will on average use electricity with a lower global warming potential due to its longer lifetime compared to a light commercial vehicle. Vehicles built in 2050 use the same decarbonised grid electricity over their entire lifetime.

For 2050, only the fully decarbonised GreenSupreme grid electricity mix is used in this study. Table 6 shows the global warming potentials for the different scenarios and years.

Table 6 : Global warming potentials of the German grid electricity mixes according to the GreenSupreme and GreenLate scenarios

Scenario	Unit	2020	2030	2040	2050
GreenLate	g CO_2eq/kWh	429*	254	158	8**
GreenSupreme	g CO_2eq/kWh	429*	113	29	8

*Electricity mix in 2020 independent of scenario; **For 2050, the value from GreenSupreme is adopted for all scenarios

Source: own calculations ifeu

For the blending of synthetic fuels, these fuels are produced using fully renewable electricity mixes in all years. For the liquid synthetic fuels, petrol and diesel, this is a mix of wind power (on- and offshore), photovoltaics and concentrating solar power in Morocco in 2020, 2030 and 2040. The gaseous fuels (synthetic natural gas and hydrogen) are produced in the same years with a mix of wind power (on- and offshore) and photovoltaics in Germany. The shares of different renewable energies are taken from the GreenLate and GreenSupreme scenarios. Table 7 shows the global warming potentials of these renewable electricity mixes. In 2050, all fuels are produced with the German electricity mix using the decarbonised background data.

Table 7 : Global warming potentials of fully renewable electricity mixes to produce synthetic fuels (background scenario: GreenSupreme)

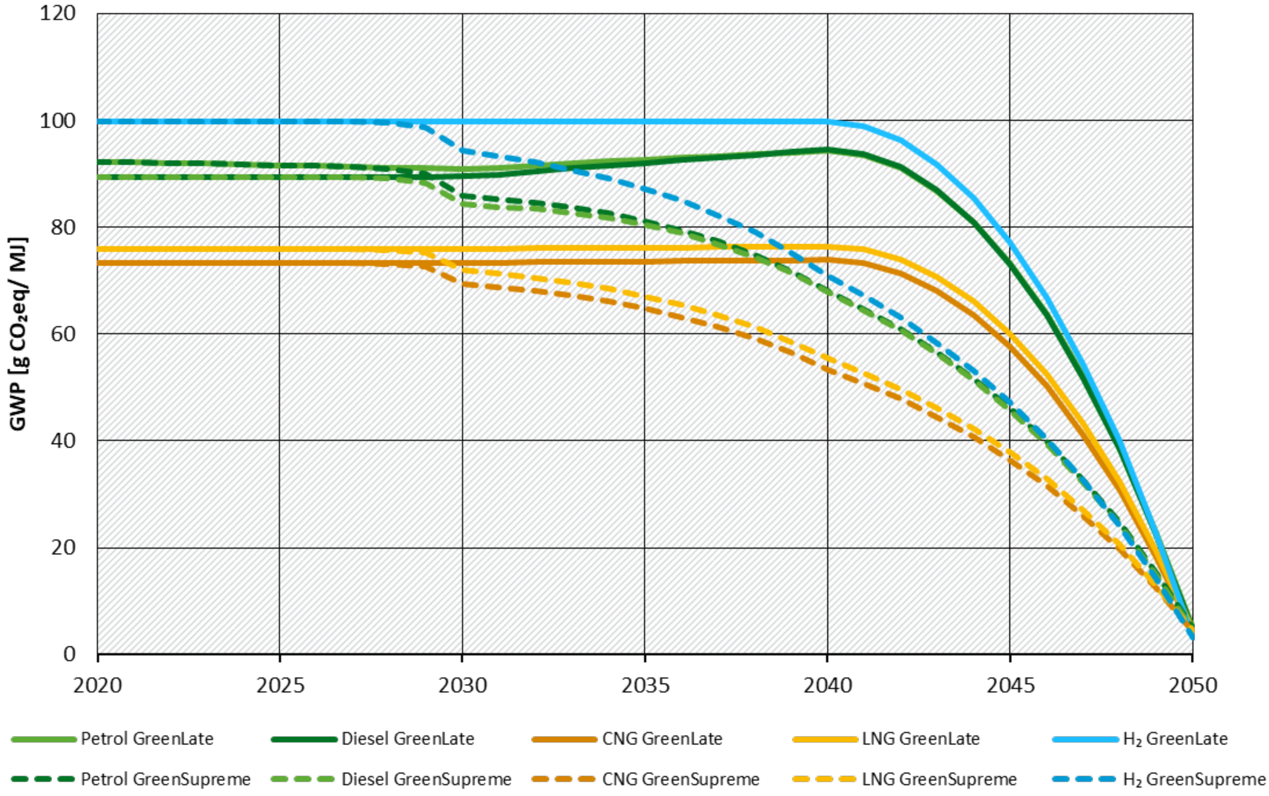
Scenario	Unit	2020	2030	2040	2050
Germany	g CO_2eq/kWh	30	11	10	8
Morocco	g CO_2eq/kWh	18	10	9	-

Source: own calculations ifeu

Not only the renewable electricity mixes used to produce the electricity-based fuels are based on the GreenLate and GreenSupreme scenarios from the UBA REFINE project, but also the shares of fossil, biogenic and synthetic fuels are derived from these scenarios. According to GreenSupreme, synthetic fuels will be available in significant quantities from 2030 onwards. According to GreenLate, introduction of synthetic fuels starts in 2040. Ramp-up of these fuels is interpolated between the different supporting years using an exponential/polynomial function, since this approximates the introduction of new technologies better than a linear function.

Figure 2 shows the global warming potentials of the fuel mixes per megajoule of lower heating value according to the GreenSupreme and GreenLate scenarios for the period from 2020 to 2050. For the years between the base years, the mixes (and thus also their global warming potentials) are interpolated. To ensure comparability between the fuels, the complete oxidation (combustion) of carbon to CO_2 is added for all fuels in this graph.

Figure 2 : Global warming potentials of the fuel mixes according to the GreenSupreme and GreenLate scenarios (incl. complete combustion) per MJ lower heating value



Source: own calculations ifeu

We would like to point out, that the upstream processes for fossil fuels in this study are still calculated without increased methane emissions from oil and gas production, even though these are referred to in the environmental goals of the United Nations and important life cycle assessment databases. If these emissions were considered, the global warming potential of fossil petrol and diesel would be about 3 g CO_2eq/MJ higher. For hydrogen, this additional burden would be around 4 g CO_2eq/MJ.

For the synthetic fuels, the following assumptions are kept constant over the years: Petrol is produced using the methanol-to-gasoline process, diesel via the Fischer-Tropsch route, CNG/LNG via direct methanation. Alkaline electrolysis is used throughout. CO_2 is captured from the air.

In the GreenLate scenarios, synthetic fuels are not added to the fuel mix until 2040 and the share of biofuels decreases from 2030 onwards; thus the GWP of petrol, diesel and CNG/LNG increases slightly and that of hydrogen stagnates until 2040. In the GreenSupreme scenario, the GWP of all fuels decreases continuously. However, the largest reduction occurs between 2040 and 2050, when the share of synthetic fuels increases from 31% to 100%.

The increase in PtL/PtG blending and the decrease in bio-blending results in different fuel mixes for each year. The fuel mixes shown in Table 8 correspond to the fuel mix the vehicle is operated with on average over its entire lifetime.

Table 8: Average blending of synthetic and bio-based fuels over the lifetime of the vehicles

Vehicle	Scenario	Share of synthetic fuels	Biodiesel share	Bioethanol share	Biomethane share
Car, YOM 2020	GreenLate	0%	7%	5.6%	0.9%
	GreenSupreme	3.1%	7%	5.6%	0.9%
Car, YOM 2030	GreenLate	2.8%	7%	5.6%	0.9%
	GreenSupreme	22.6%	7%	5.6%	0.9%
Car, YOM 2050	GreenSupreme	100%	0%	0%	0%
LCV, YOM 2020	GreenLate	0%	7.6%	5.7%	1.0%
	GreenSupreme	1.7%	7.6%	5.7%	1.0%
LCV, YOM 2030	GreenLate	0.7%	3.5%	3.5%	0.5%
	GreenSupreme	18.0%	3.5%	3.5%	0.5%
LCV, YOM 2050	GreenSupreme	100%	0%	0%	0%
LCV, YOM 2020	GreenLate	0%	7.6%	5.3%	1.0%
	GreenSupreme	0%	7.6%	5.3%	1.0%
LCV, YOM 2030	GreenLate	0%	5.2%	5.1%	0.7%
	GreenSupreme	10.6%	5.2%	5.1%	0.7%
LCV, YOM 2050	GreenSupreme	100%	0%	0%	0%

Source: own calculations ifeu

Developments in the background system

We assume that the economy in Germany and the rest of the world will be decarbonised as far as possible until 2050. Therefore, materials and intermediate products for the production of vehicles as well as the generation infrastructure of electricity from renewable sources will have lower emissions than today. To depict such a development, a background system that is decarbonised as far as possible is used for all vehicles built in 2050. It is based on the REFINE results for the year 2050 (GreenSupreme). For other processes such as the materials for the construction of electricity generation plants, CO_2 capture and synthesis plants, and transport processes, a partially decarbonised background system according to GreenSupreme is already used for the year 2030.

Summary

These basic assumptions lead to the following standard cases:

- Vehicles produced in 2020 ("starting point") with average electricity/fuel mixes according to GreenLate (and GreenSupreme as a sensitivity calculation).

- Vehicles produced in 2030 ("transition phase") with average electricity/fuel mixes according to GreenLate and to GreenSupreme.
- Vehicles produced in 2050 depicting a decarbonised end point ("GHG neutrality") based on the GreenSupreme scenario.

All considered combinations as well as their abbreviations are listed in Table 9.

Table 9: Standard cases considered

Year of manufacture	Electricity/Fuels	Background system	Abbreviation (short)
2020	GreenLate/ GreenSupreme	Today	YOM 2020 GL/GS
2030	GreenLate/ GreenSupreme	Vehicles: Today (battery/PEMFC technology 2030) Infrastructure: GreenSupreme 2030	YOM 2030 GL/GS
2050	GreenSupreme	GreenSupreme 2050	YOM 2050 GS

In the graphs (Figure 12 to Figure 15) the individual life cycle stages are depicted to show their influence on the overall result. The following breakdown is used:

- Veh (base): refers to the production of the vehicle (including body and powertrain) but without the traction battery.
- Battery: refers to the production of the traction battery
- Electricity/fuel: refers to the electricity and fuel supply (including the charging and filling station infrastructure as well as the overhead-catenary infrastructure for the O-trucks).
- Use emissions: refers to the direct exhaust emissions as well as the abrasion emissions (e.g. from brake and tyre abrasion) of the vehicles in operation (purely electric vehicles do not cause any direct exhaust emissions, but are nevertheless responsible for emissions from abrasion, which have a similar level as in conventional vehicles).
- Maintenance: refers to the maintenance of the vehicles
- EoL: End of Life refers to the disposal of the vehicle including the traction battery.

All emission values given are always per vehicle kilometre, assuming a uniform average load of 11 t for the heavy-duty vehicles.

3 Results

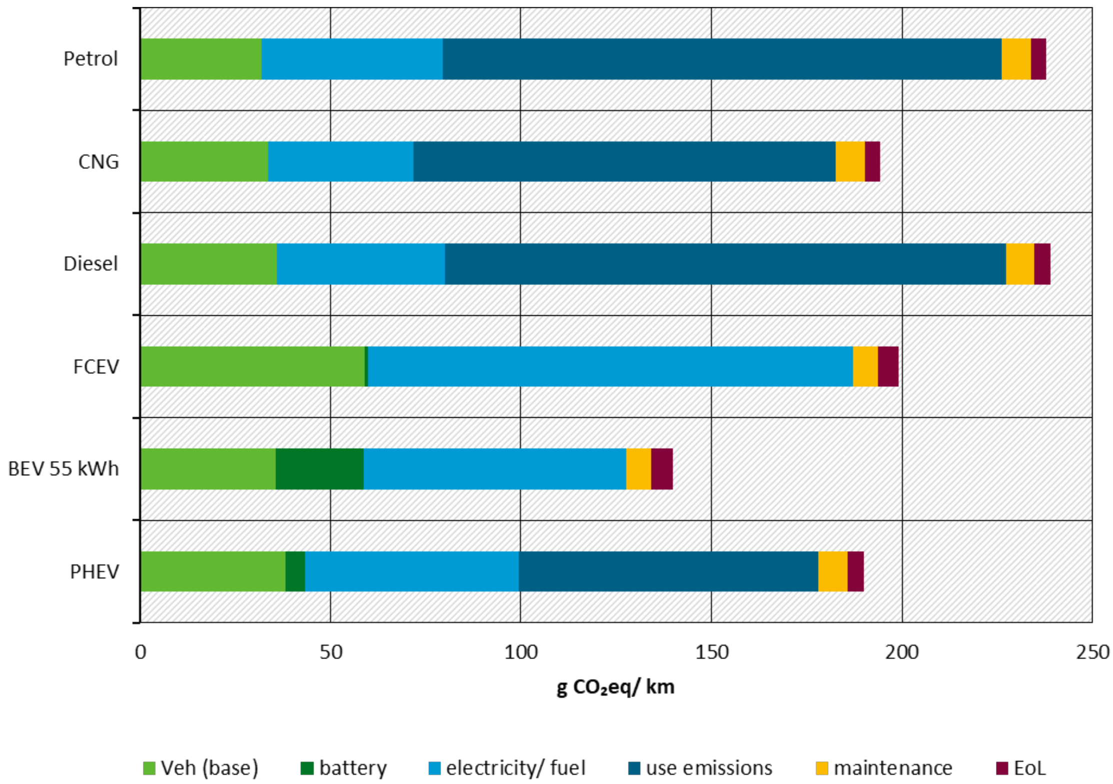
3.1 Global warming potentials

3.1.1 Passenger cars and light commercial vehicles

Passenger car with year of manufacture 2020 (starting point)

In Figure 3 the results for passenger cars built in 2020 are shown using the less ambitious GreenLate scenario. Here, vehicles with conventional petrol or diesel engines have the highest global warming potential per vehicle kilometre. Despite the efficiency advantages of diesel engines compared to petrol engines, an average compact-class diesel car has a comparable global warming potential of 239 g CO_2eq per km compared to a petrol car with 238 g CO_2eq per km. The is due to the greater weight and higher motor power of current diesel compact-class cars. Natural gas-powered cars perform better with 194 g CO_2eq per km, due to the lower fuel consumption of current models. The FCEV passenger car has a global warming potential of 199 g CO_2eq per km and the PHEV passenger car of 190 g CO_2eq per km, which are very similar to the CNG passenger car. Currently, they have only minor advantages over petrol and diesel passenger cars. One reason for this is that the hydrogen for fuel cell vehicles generally comes from reforming of fossil natural gas today. In the case of plug-in hybrids, it is primarily the relatively low proportion of electric driving in real-world operation that leads to a similar balance as the CNG or FCEV passenger cars. The lowest global warming potential of 140 g CO_2eq per km is currently shown by the electric car (with a 55-kWh battery), which is 41% lower than for the petrol car.

Figure 3 **Global warming potential of compact class cars (year of manufacture 2020, scenario GreenLate)**



Source: own calculations ifeu

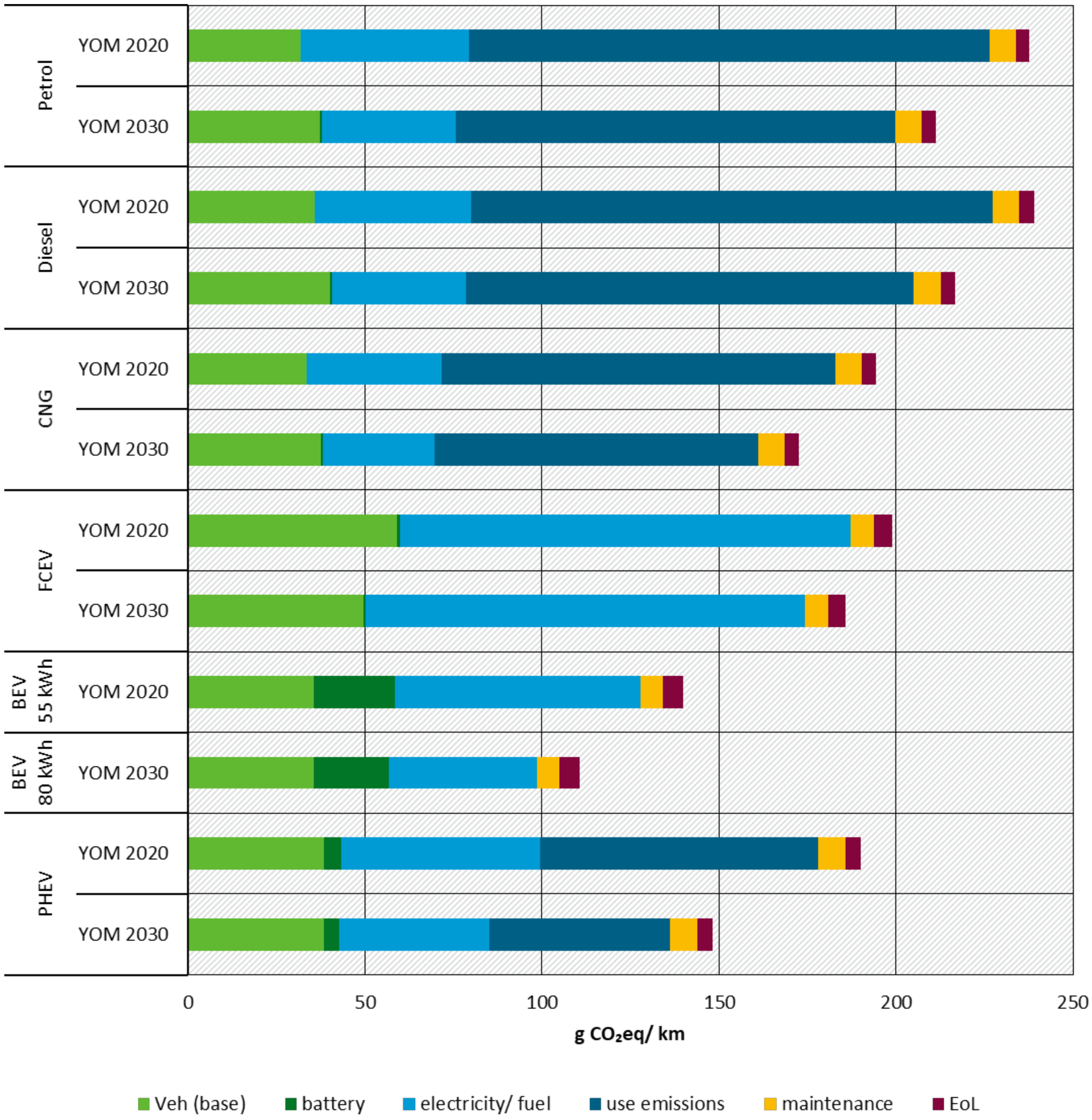
An analysis of the contributions of the individual life cycle stages shows that use emissions currently have the largest contribution to the greenhouse gas emissions of passenger cars with internal combustion engines. For diesel and petrol cars, these are 147 g CO_2eq per km[1]. The use emissions of CNG cars are lower with 111 g CO_2eq per km and those of plug-in hybrids are at 79 g CO_2eq per km. The second largest item for conventional passenger cars and the largest item for passenger cars with alternative drivetrains is the provision of electricity and fuels. Vehicle production (including the production of the traction battery for electric vehicles) also plays a role; the contributions are significantly higher for passenger cars with alternative drivetrains than for conventional ones. For all vehicle types, maintenance and end-of-life have the lowest impact on the global warming potential.

Passenger car with year of manufacture 2030 (transition phase)

Figure 4 shows how the global warming potential per vehicle kilometre of compact-class passenger cars could develop in the future. Passenger cars with conventional drivetrains with year of manufacture 2030 improve only slightly compared to the year of manufacture 2020 in the scenario GreenLate. This decrease in emissions is mainly due to reductions in energy consumption (e.g. due to hybridisation), which clearly overcompensates the additional burdens in vehicle production. In the GreenLate scenario no renewably produced fuels will be available for vehicle operation by 2030, thus the use emissions otherwise barely change. In contrast, as renewable electricity becomes more widely available both the Plug-In-Hybrid (for the electric driving share, which also increases slightly) and the battery-electric vehicle benefit from the lower global warming potential from electricity generation in Germany. Despite a larger traction battery, the advantage of the BEV car built in 2030 in terms of global warming potential per kilometre increases to 49% compared to the petrol-powered car of the same year of manufacture.

[1] In this study, the total life cycle emissions are considered. In contrast, the fleet target values only include the direct (tank-to-wheel) exhaust emissions. For comparison: This official fleet target value for passenger cars in Germany was 95 g CO_2/km in 2020, whereby battery-electric passenger cars are counted with zero emissions.

Figure 4: Global warming potential of compact class cars (year of manufacture 2020 and 2030, GreenLate scenario)

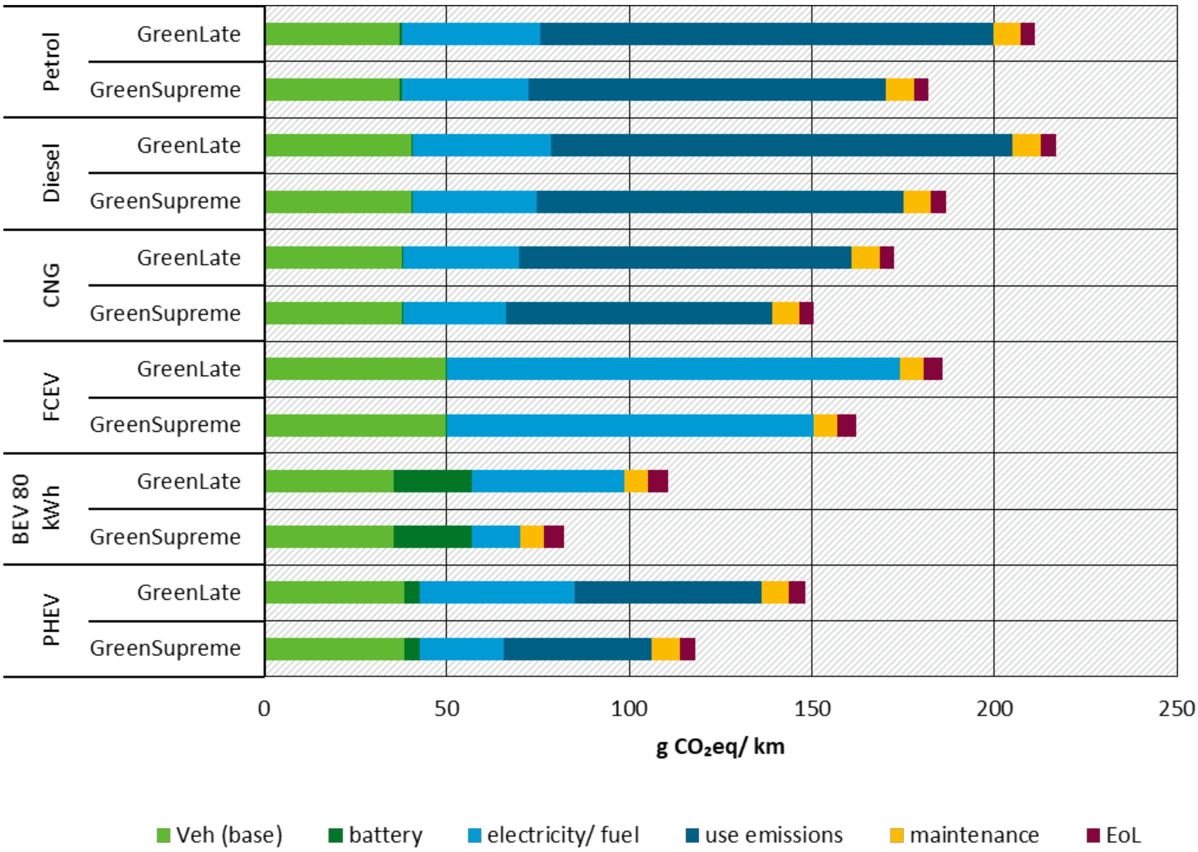


Source: own calculations ifeu

The analysis of the contributions of the life cycle stages shows no major shifts for the year of manufacture 2030 compared to the year of manufacture 2020. The only exception is the BEV passenger car, where the contribution of vehicle production and traction battery in the year of manufacture 2030 is higher than the contribution of electricity supply. This is partly due to the fact that for vehicle and traction battery production the background system is still at the current level and only technological improvements are assumed, while the shares of renewable energy in the electricity mix are already relatively high. In the case of BEV passenger cars, the absolute contributions of the traction batteries hardly differ between the model years, as the additional impacts for the production of the larger battery and the improvements due to the changed cell chemistry and improved cell production offset each other, although the vehicle range increases significantly. For the fuel cell car, there is a decrease in the contribution of vehicle production compared to the year of manufacture 2020 due to the fuel cell with lower platinum loading.

Figure 5 compares the two scenarios, GreenLate and GreenSupreme, for compact cars built in 2030. Differences therefore only lie in the fuel and electricity supply, as well as the direct use emissions due to the higher PtX share. Here, there are clear differences for all drivetrains between the GreenLate and GreenSupreme scenarios, as the global warming potential decreases with the accelerated shift to renewable energies and the increased blending of PtX fuels made from renewable energy. For example, a petrol-powered car built in 2030 in GreenSupreme sees an average PtX share of 22.6% over its life cycle compared to only 2.8% in GreenLate. Nevertheless, the electric car in particular benefits disproportionately from the higher share of renewables in the German electricity mix. While the BEV car built in 2030 has a 45% lower global warming potential than the petrol-powered car in the GreenLate scenario, the difference is 52% in the GreenSupreme scenario.

Figure 5: Global warming potential of compact class cars (year of manufacture 2030, GreenLate and GreenSupreme scenarios)

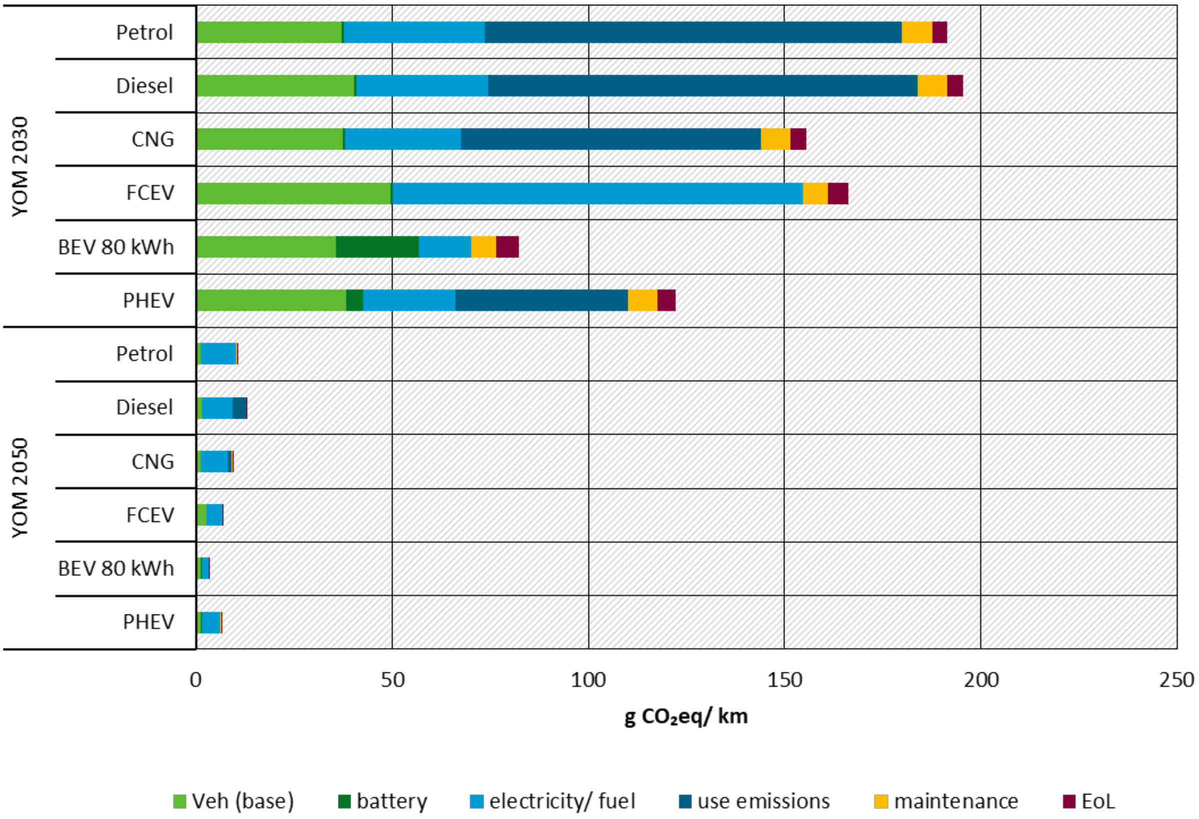


Source: own calculations ifeu

Passenger car with year of manufacture 2050 (GHG neutrality)

Figure 6 shows the global warming potential in a decarbonised world according to the GreenSupreme scenario in 2050. It shows a reduction in the global warming potential per vehicle kilometre for all vehicle types of more than 90% compared to the year of manufacture 2030 (or at least 95% compared to the year of manufacture 2020 GreenLate). The BEV passenger car has the most favourable balance due to its higher overall energy efficiency. The use emissions decrease most strongly, only for diesel cars the nitrous oxide emissions that occur due to denitrification are still noticeable. All other remaining (and unavoidable) greenhouse gas emissions are determined by the provision of the decarbonised fuels and, to a lesser extent, by the production of the vehicles.

Figure 6: Global warming potential of compact class cars (year of manufacture 2030 and 2050, GreenSupreme scenario)



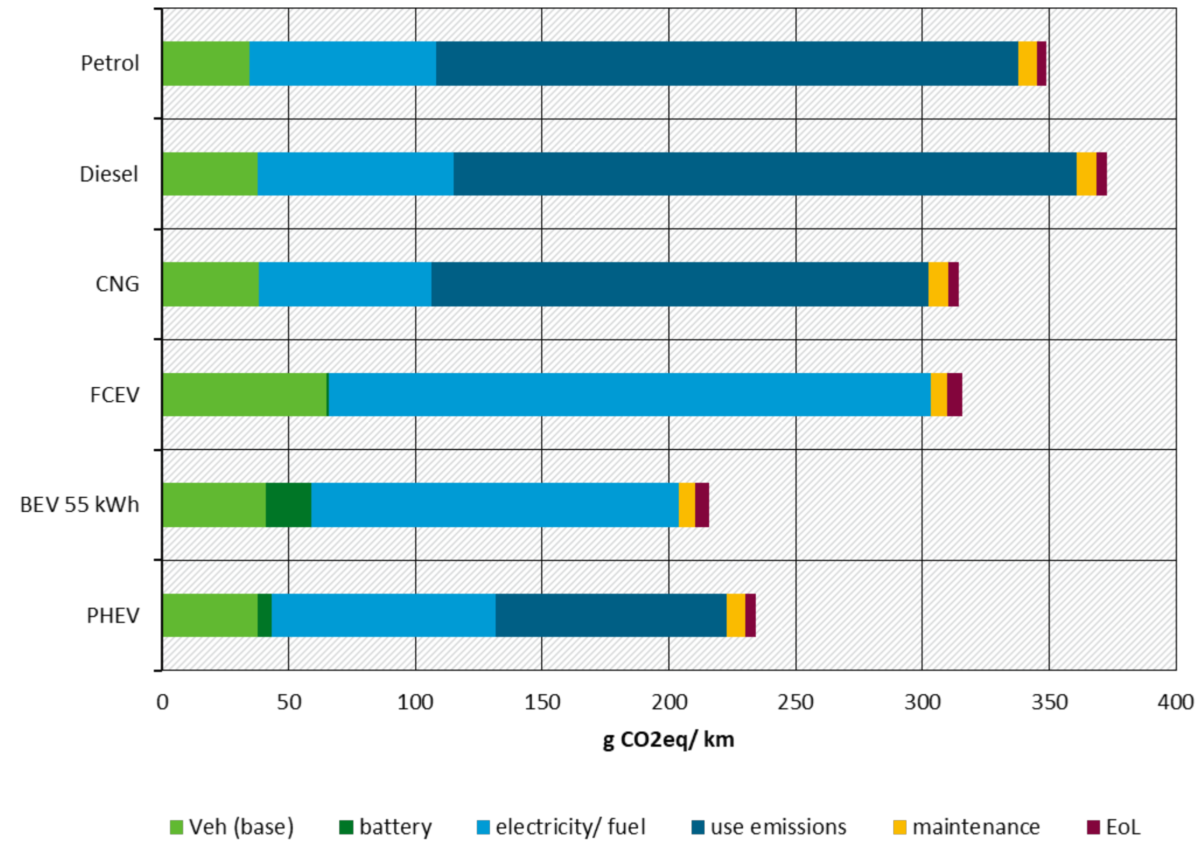
Source: own calculations ifeu

Light commercial vehicles

Light commercial vehicles show similar trends as passenger cars; thus, they are presented in less detail here.

For light commercial vehicles with year of manufacture 2020 (shown in Figure 7), the battery electric vehicle has the lowest global warming potential with currently 216 g CO_2eq per km. This is 42 % lower than the diesel LCV which has the highest global warming potential of 373 g CO_2eq per km. At 349 g CO_2eq per km, the petrol LCV is slightly better than the diesel LCV, and the CNG and FCEV LCV perform even better with 315 g CO_2eq per km. At 235 g CO_2eq per km, the Plug-In Hybrid is only slightly worse than the battery-electric vehicle. Thus, the gap between PHEV and BEV is lower than for passenger cars. This is mainly due to the fact that the share of urban trips is higher for light commercial vehicles than for passenger cars. Therefore, the Plug-In Hybrid has a more favourable application profile - it can achieve higher electric driving shares and benefits from recuperation in urban traffic.

Figure 7: Global warming potential of LCV N1-III (year of manufacture 2020, GreenLate scenario)



Source: own calculations ifeu

The further trends for light commercial vehicles strongly follow those for passenger cars. Global warming potentials decrease in later years of manufacture, especially when an ambitious expansion of renewable energies is assumed, with battery-electric vehicles again benefiting the most.

3.1.2 Heavy-duty trucks

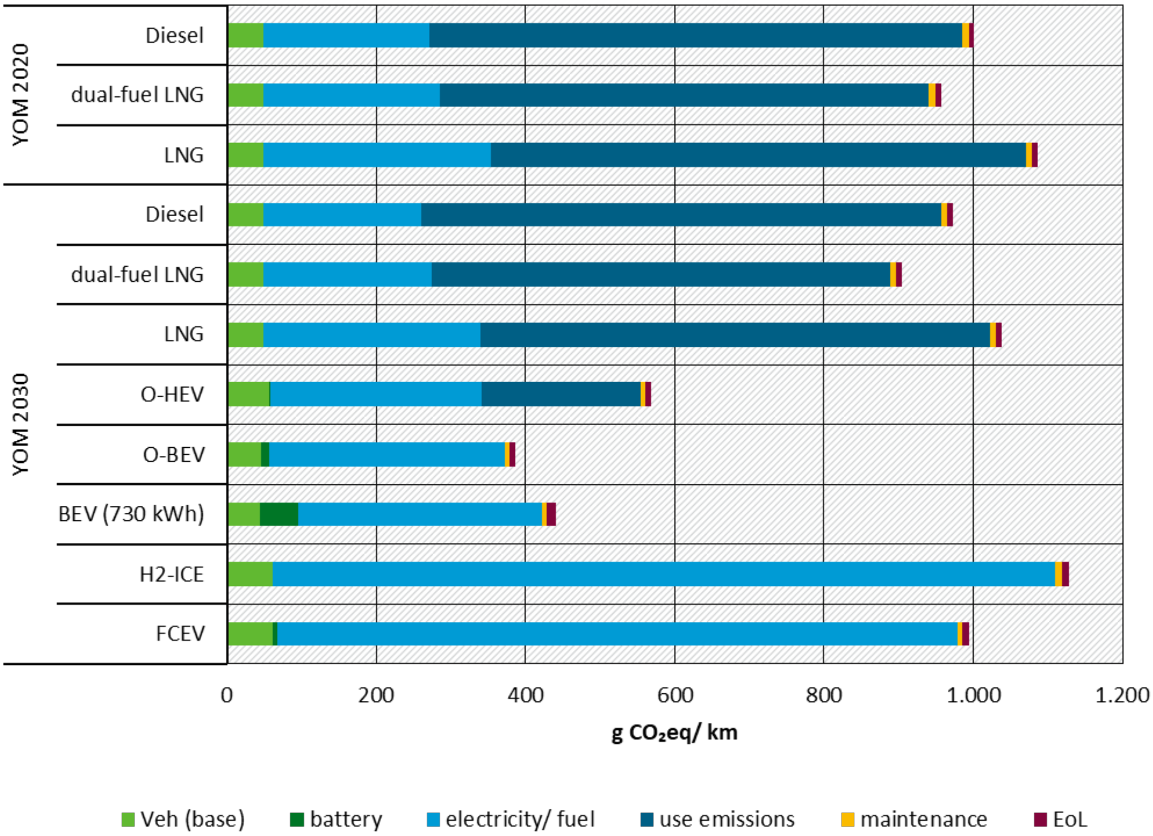
Heavy-duty trucks with year of manufacture 2020 ("starting point") as well as 2030 ("transition phase")

As shown in Figure 8, a tractor-trailer truck with a gross vehicle weight of 40 t has a global warming potential of around 1000 g CO_2eq /km (of which 937 g CO_2eq/km are attributable to diesel combustion and supply). This corresponds to a global warming potential of 83 g CO_2eq per tonne-kilometre for the diesel tractor-trailer truck built in 2020. While the dual- fuel LNG truck performs 5% better than the diesel truck, the LNG truck has an 8% higher global warming potential due to its lower engine efficiency. For the vehicles with year of manufacture 2030, there will be slight improvements in the fuel efficiency for trucks with conventional drivetrains, but this will not change the ranking of the different powertrains. A truck built in 2030 still has a global warming potential of 973 g CO_2eq/km in the GreenLate scenario. All trucks with alternative drivetrains except the fuel cell and H2-ICE truck have a significantly lower global warming potential compared to conventional vehicles. The O-BEV has the lowest global warming potential of 386 g CO_2eq/km, as it is powered exclusively by electricity but requires a smaller traction battery due to the overhead line network than the BEV truck with 440 g

CO_2eq/km. The O-HEV is attractive as a bridging technology in the year of manufacture 2030 and lies at 569 g CO_2eq/km, assuming that the overhead line network on the German motorways has been expanded to such an extent that the truck can be driven on them using only electricity.

The fuel cell truck and the H2-ICE truck built in 2030 have no advantages over the diesel truck, as they are fuelled (almost) entirely with hydrogen from steam reforming of fossil natural gas.

Figure 8: Global warming potential of trtactor-trailer trucks (year of manufacture 2020 and 2030, GreenLate scenario) with average load (11 t payload)

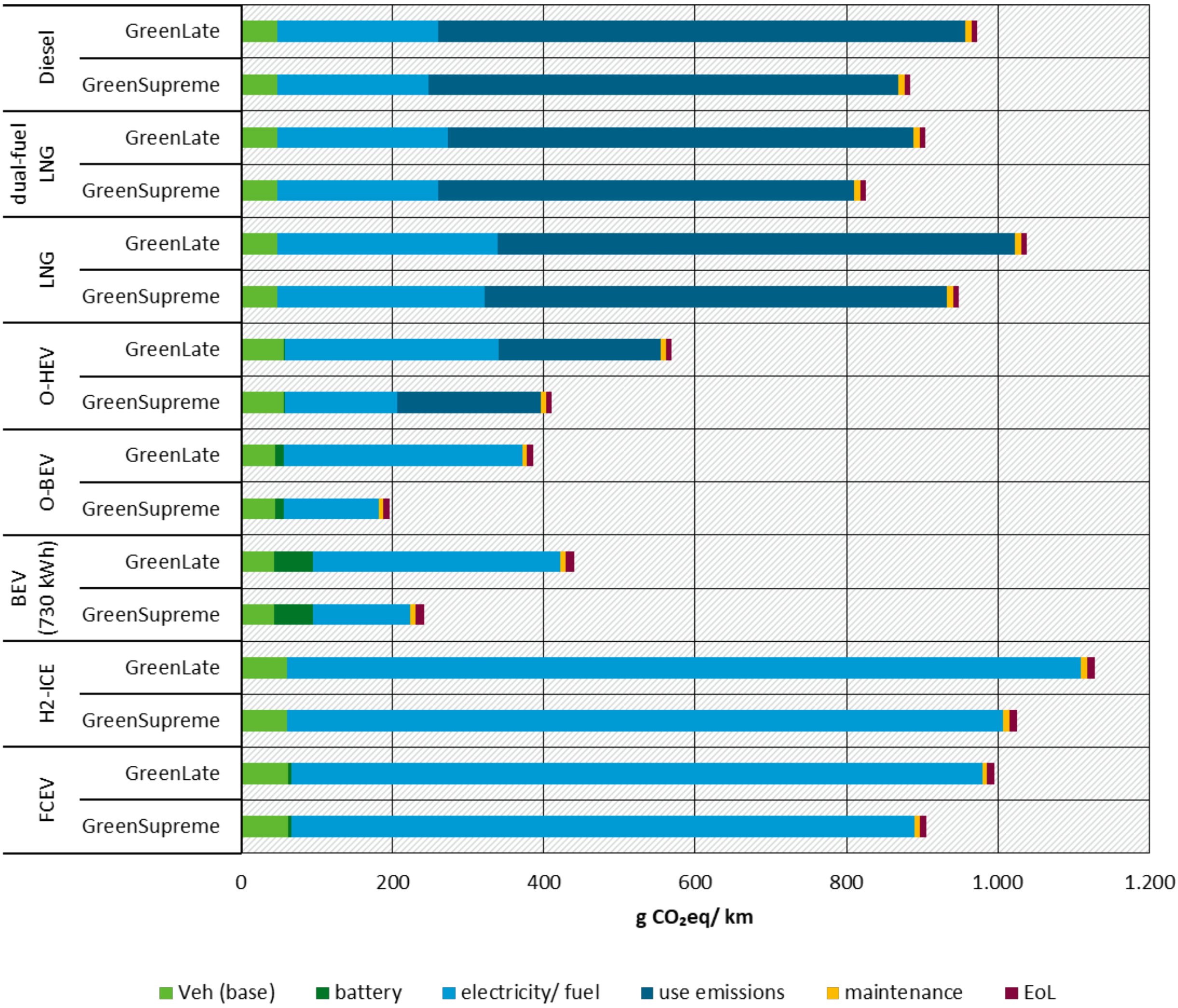


Source: own calculations ifeu

When the contributions of the different life cycle stages are examined, it becomes apparent that fuel combustion and provision of fuel and electricity dominate the global warming potential even more than for passenger cars. More than 90% of the global warming potential of trucks with fossil fuels is attributable to these life cycle stages. Even for BEV trucks the provision of electricity still accounts for 75% of the overall global warming potential. This is due to the fact that the impacts from manufacturing are depreciated over many kilometres due to the high mileage of the heavy-duty trucks.

In Figure 9, the global warming potentials of heavy-duty trucks built in 2030 in the scenarios GreenLate and GreenSupreme are compared. Here all vehicles benefit from a faster shift towards renewable energies in GreenSupreme. The electric-using heavy-duty trucks (BEVs and O-BEVs) benefit most from the overall development, as the electricity used to power them already mainly comes from renewables. At the same time the quantities of electricity-based fuels are limited and mainly fossil fuels are used. Thus, BEVs as well as O-BEVs can increase their advantage in global warming potential in the GreenSupreme scenario compared to diesel heavy-duty trucks to -73% and -78%, respectively. The FCEV and H2 -ICE heavy-duty trucks as well as the LNG heavy-duty truck continue to have disadvantages compared to the diesel heavy-duty truck, as a fuel-independent PtG/PtL share is assumed. Only if renewable hydrogen can be made available earlier in larger quantities than PtL diesel, this picture could change.

Figure 9: Global warming potential of the tractor-trailer trucks (year of manufacture 2030, GreenLate and GreenSupreme scenarios) with medium load (11 t payload)

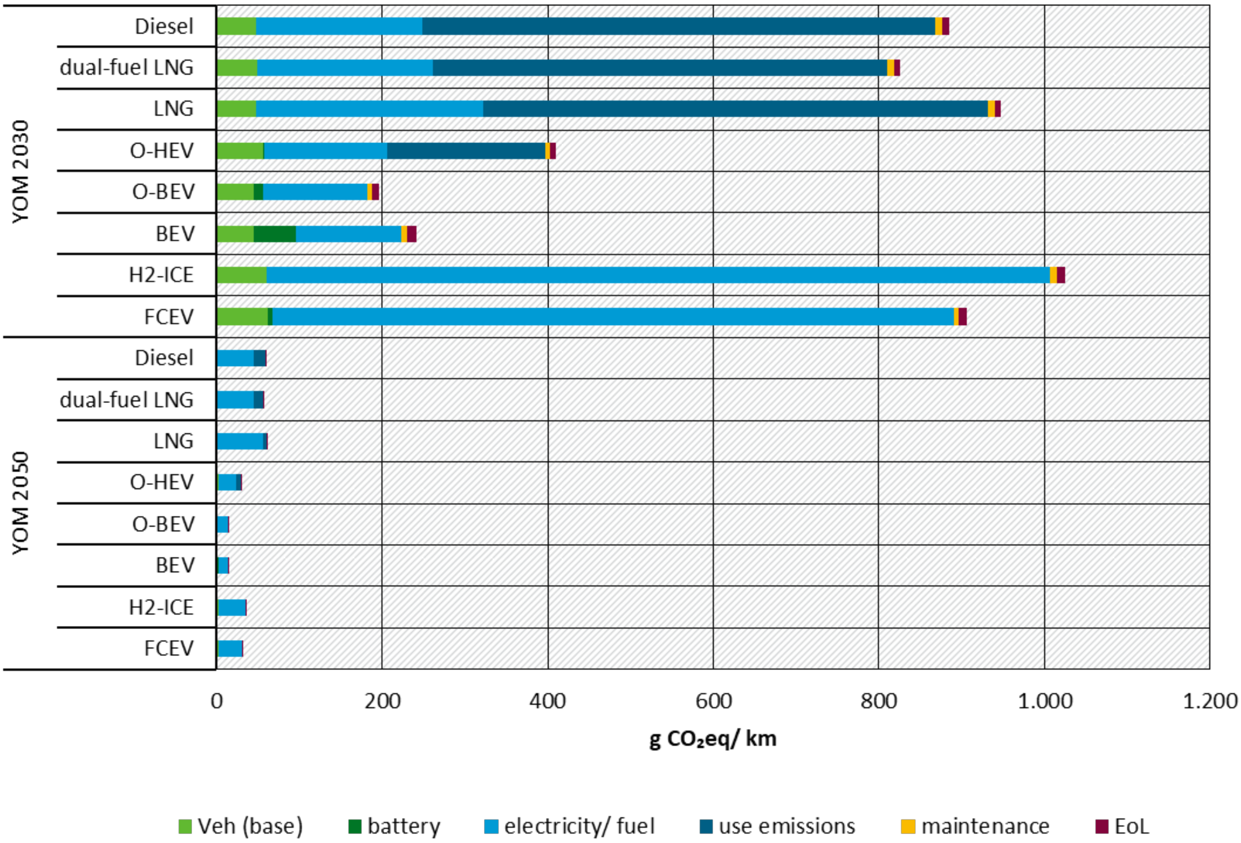


Source: own calculations ifeu

Heavy-duty trucks with year of manufacture 2050 ("GHG neutrality")

In the GreenSupreme scenario, the global warming potentials for heavy-duty trucks are also reduced by more than 90% due to the complete decarbonisation by 2050 compared to the 2030 year of manufacture. As shown in Figure 10, the O-BEV remains the concept with the lowest global warming potential. The remaining greenhouse gas emissions stem mainly from fuel and electricity supply.

Figure 10: Global warming potential of heavy-duty trucks (year of manufacture 2030 and 2050, GreenSupreme scenario) with medium load (11 t payload)



Source: own calculations ifeu

3.2 Normalized environmental impacts

The discussion about Germany's medium- and long-term climate protection goals in the transport sector naturally focuses on the comparison of the global warming potentials of the different drivetrain options. In addition to this impact category, other environmental impacts also play a significant role in assessing the impact of road traffic on nature and people. In this section, the environmental impacts of passenger cars, light commercial vehicles and heavy-duty vehicles are assessed in a total of eight environmental categories and three resource categories per vehicle kilometre.

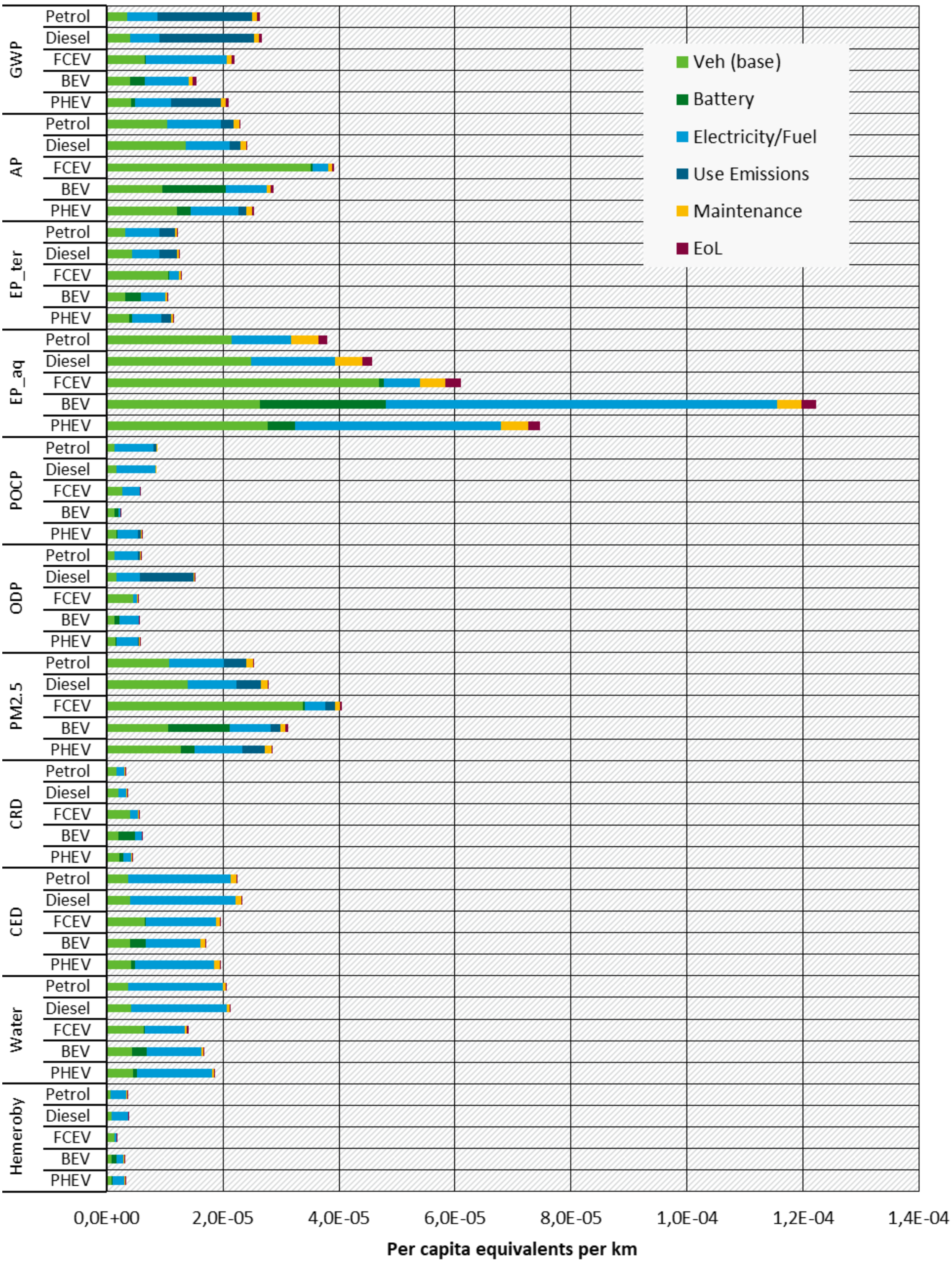
In order to estimate how relevant the additional burdens in these categories are, their size is related to the current environmental burden. The starting point for the normalisation is the current environmental impact per capita in Germany. In order to improve the readability of the graphs and because very similar trends can be observed in some cases, not all powertrain concepts are always shown. The focus for passenger cars lies on petrol-/diesel-powered cars and cars with alternative drivetrains, and for heavy-duty vehicles on diesel/dual-fuel trucks and trucks with alternative drivetrains. Plug-in hybrids and CNG cars are only dealt with explicitly in individual cases. The same applies to pure LNG vehicles and overhead-catenary hybrid electric trucks.

3.2.1 Passenger cars and light commercial vehicles

Figure 11 shows the normalised results for compact class cars built in 2020 using the average electricity and fuel mixes according to the GreenLate scenario per vehicle kilometre for all impact categories investigated.

The following impact categories are particularly relevant with regard to the total impact per capita in Germany: aquatic eutrophication (EP_aq), particulate matter formation (PM2.5), acidification (AP) and global warming potential (GWP). The resource categories cumulative energy demand (CED) and freshwater demand are also of higher significance. The environmental impact categories in which compact cars built in 2020 in Germany contribute less to the overall burden are terrestrial eutrophication (EP_ter), photochemical ozone creation (POCP), ozone depletion (ODP) and the resource categories cumulative raw material demand (CRD) and land use (hemeroby).

Figure 11 : Normalised results of all environmental impact categories investigated for compact class cars (year of manufacture 2020, GreenLate scenario)

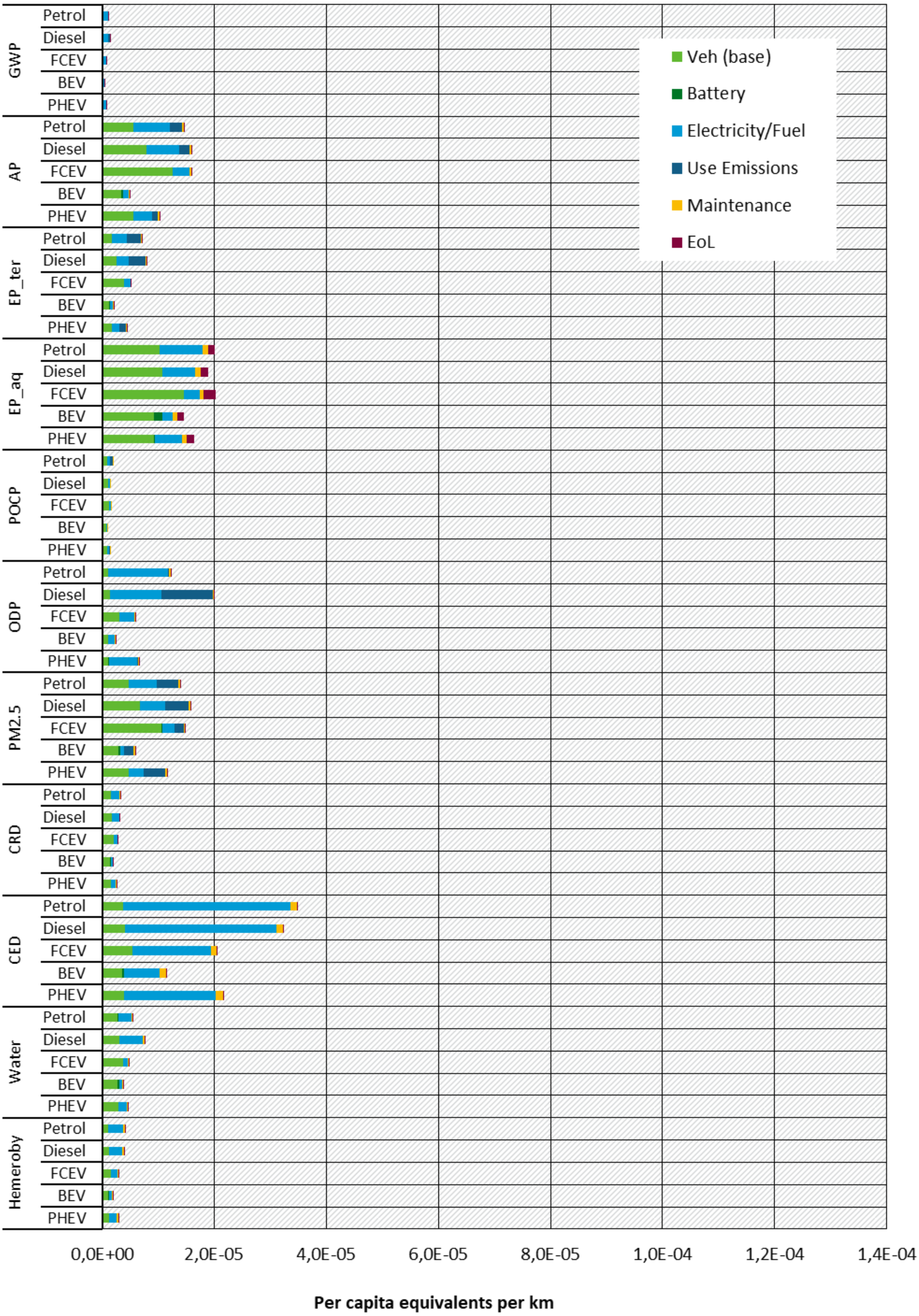


Source: own calculations ifeu

Direct use emissions account for the largest contributions in only two impact categories: the global warming potential of vehicles using fossil fuels and the ozone depletion potential of diesel passenger cars. The latter is a consequence of the denitrification of exhaust gases, which produces ozone-depleting nitrous oxide (N_2O). To a lesser extent, direct emissions also contribute to acidification (ammonia and nitrogen oxides), terrestrial eutrophication (nitrogen oxides) and to particulate matter formation (tyre abrasion).

In almost all other impact categories, vehicle production including the traction battery, as well as the provision of fuels are responsible for the greatest environmental impacts. There are minor differences between the different drivetrains, but these are not uniformly observed and only few categories show bigger differences. For example, the production of the traction battery of BEV and PHEV vehicles contributes strongly to acidification, aquatic eutrophication and particulate matter formation. Main causes are the emissions from the production of copper and nickel. For the FCEV, vehicle production contributes more to acidification, aquatic eutrophication and particulate matter formation than vehicle production for the other drivetrains. The main cause are the emissions from platinum production.

Figure 12: Normalised results of all environmental impact categories investigated for compact class passenger cars (year of manufacture 2050, scenario GreenSupreme)



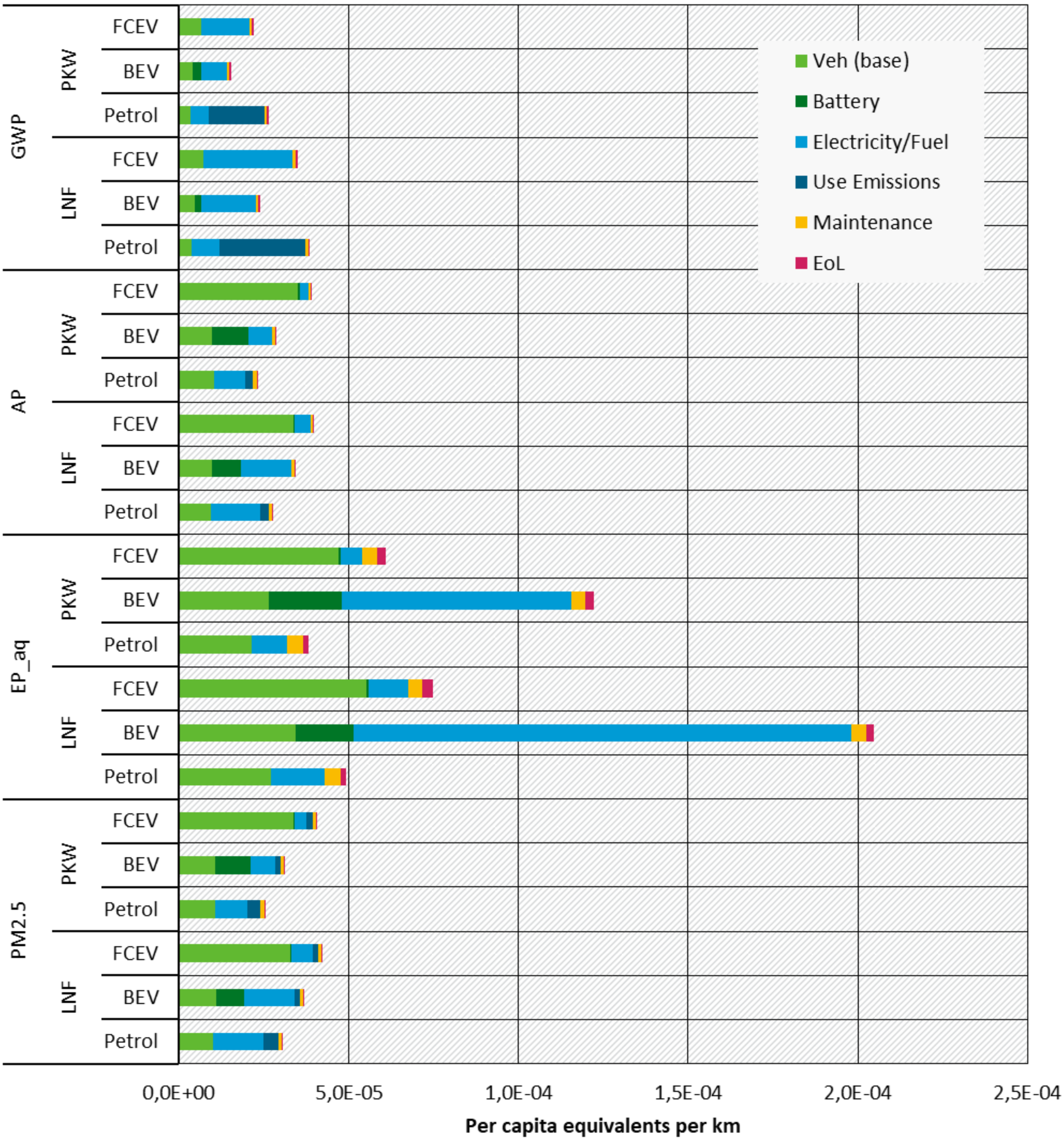
Source: own calculations ifeu

Figure 12 shows the normalised results of all analysed environmental impact categories for compact class cars with year of manufacture 2050 and average electricity or fuel mixes according to the GreenSupreme scenario 2050.

Compared to 2020, the total impact decreases in almost all impact categories - especially in the important environmental impact categories acidification, aquatic eutrophication and particulate matter formation, the latter remains the categories with the highest impact. Global warming potential (GWP) is no longer the leading category. Vehicle and fuel production now dominate all impact categories. Ozone depletion potential increases slightly for all powertrains except BEV. The main contribution to the ozone depletion potential is the production of electricity-based fuels , only for the diesel car are the higher emissions from the exhaust denitrification still evident in this category. The cumulative energy demand also increases for all drivetrains except BEVs. The largest contributions here are also made by the electricity-based fuels.

The intermediate year 2030 and the alternative development according to the GreenSupreme scenario are not presented in detail here. For petrol and diesel, values shift only slightly between 2020 and 2030. The burden of vehicle production increases slightly for them due to hybridisation. The contribution of fuels decreases by a similar order of magnitude due to improvements in consumption, a decreasing share of biofuels and - in the GreenSupreme scenario - the blending of electricity-based fuels. For the battery electric vehicle, only the contribution of electricity for propulsion changes between 2020 and 2030 and the two scenarios. Above all, the impact in the aquatic eutrophication category decreases significantly, as the leaching from coal mining also decreases with the decarbonisation of grid electricity. The impacts of vehicle production remain approximately the same, despite a larger battery due to improvements in battery production.

Figure 13 : Normalised results of selected environmental impact categories for light commercial vehicles and compact class passenger cars (year of manufacture 2020, GreenLate scenario)



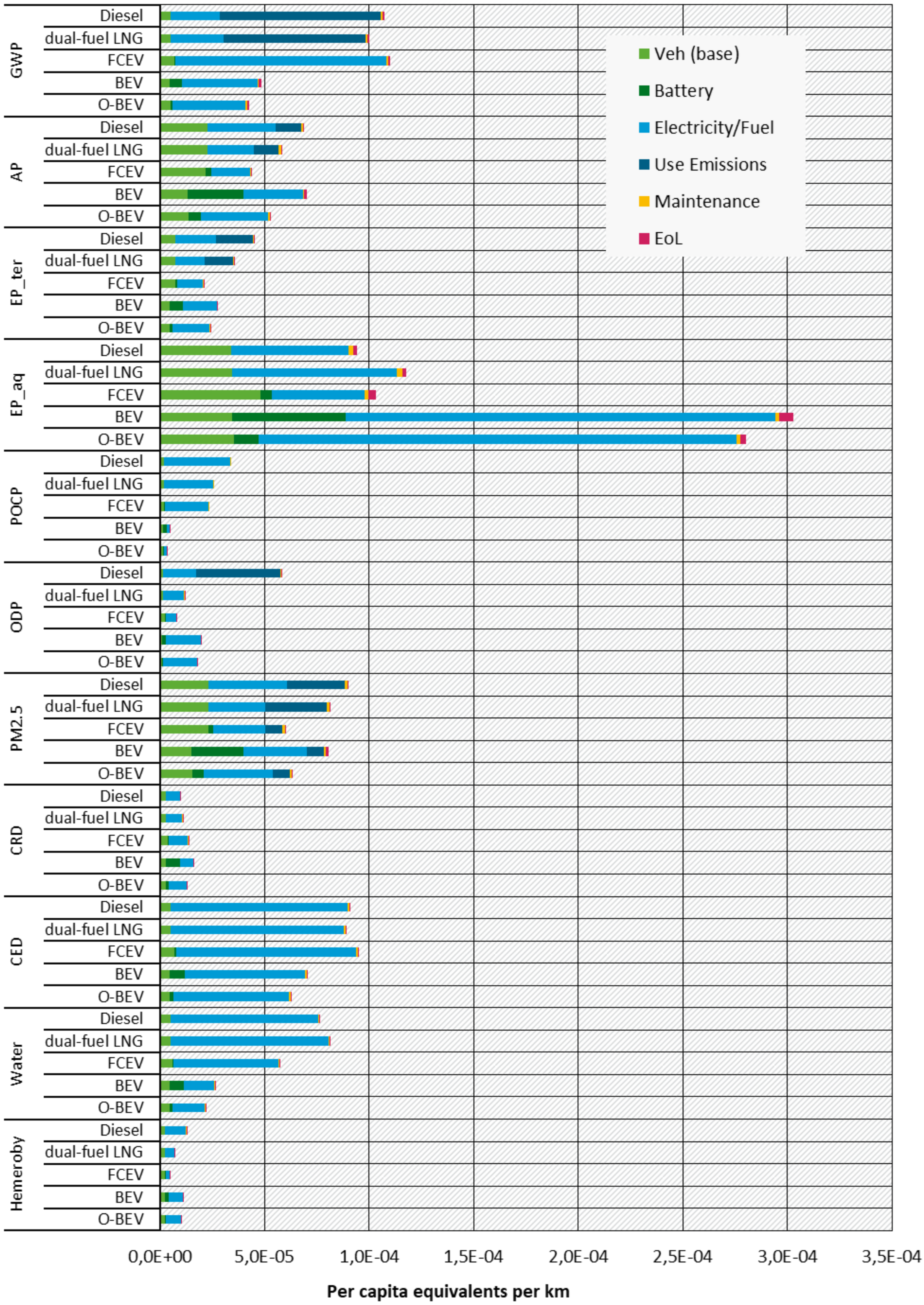
Source: own calculations ifeu

Figure 13 shows the normalised results of the most important environmental impact categories for light commercial vehicles with year of manufacture 2020 compared to compact class passenger cars of the same year of manufacture. A similar pattern emerges in the contributions of the respective environmental impact categories - with slightly higher emissions per vehicle kilometre throughout for the light commercial vehicles.

3.2.2 Heavy-duty trucks

Figure 14 shows the normalized results of all environmental and resource categories examined for heavy-duty vehicles with a medium load, year of manufacture 2030 and average electricity and fuel mixes according to the GreenLate scenario. Similar to passenger cars and light duty vehicles, the following impact categories are important: aquatic eutrophication (EP_aq), particulate matter formation (PM2.5), acidification (AP) and global warming potential (GWP). The resource categories cumulative energy demand (CED) and freshwater demand are also of higher significance. The impact categories in which heavy-duty vehicles built in 2030 in Germany contribute less to the overall impact are terrestrial eutrophication (EP_ter), photochemical ozone creation (POCP), ozone depletion (ODP) and the resource categories cumulative raw material demand (CRD) and hemeroby. However, the values are three to four times higher than for passenger cars.

Figure 14 : Normalised results of all examined environmental and resource categories for heavy-duty trucks with 11 t payload (year of manufacture 2030, GreenLate)



Source: own calculations ifeu

Direct use emissions contribute more strongly than in the case of passenger cars to the impact categories acidification (ammonia and nitrogen oxides), terrestrial eutrophication (nitrogen oxides) and particulate matter formation (tyre wear) and also dominate the global warming potential. In the ozone depletion category, N_2O emissions from diesel engine exhaust denitrification are also the biggest polluters for heavy-duty vehicles.

As with passenger cars, vehicle and fuel production are the other two major sources of environmental impacts. Maintenance and end-of-life play an even smaller role than for passenger cars. While vehicle production is more important for passenger cars, the provision of fuel is more important for heavy-duty trucks because of their much higher lifetime mileage.

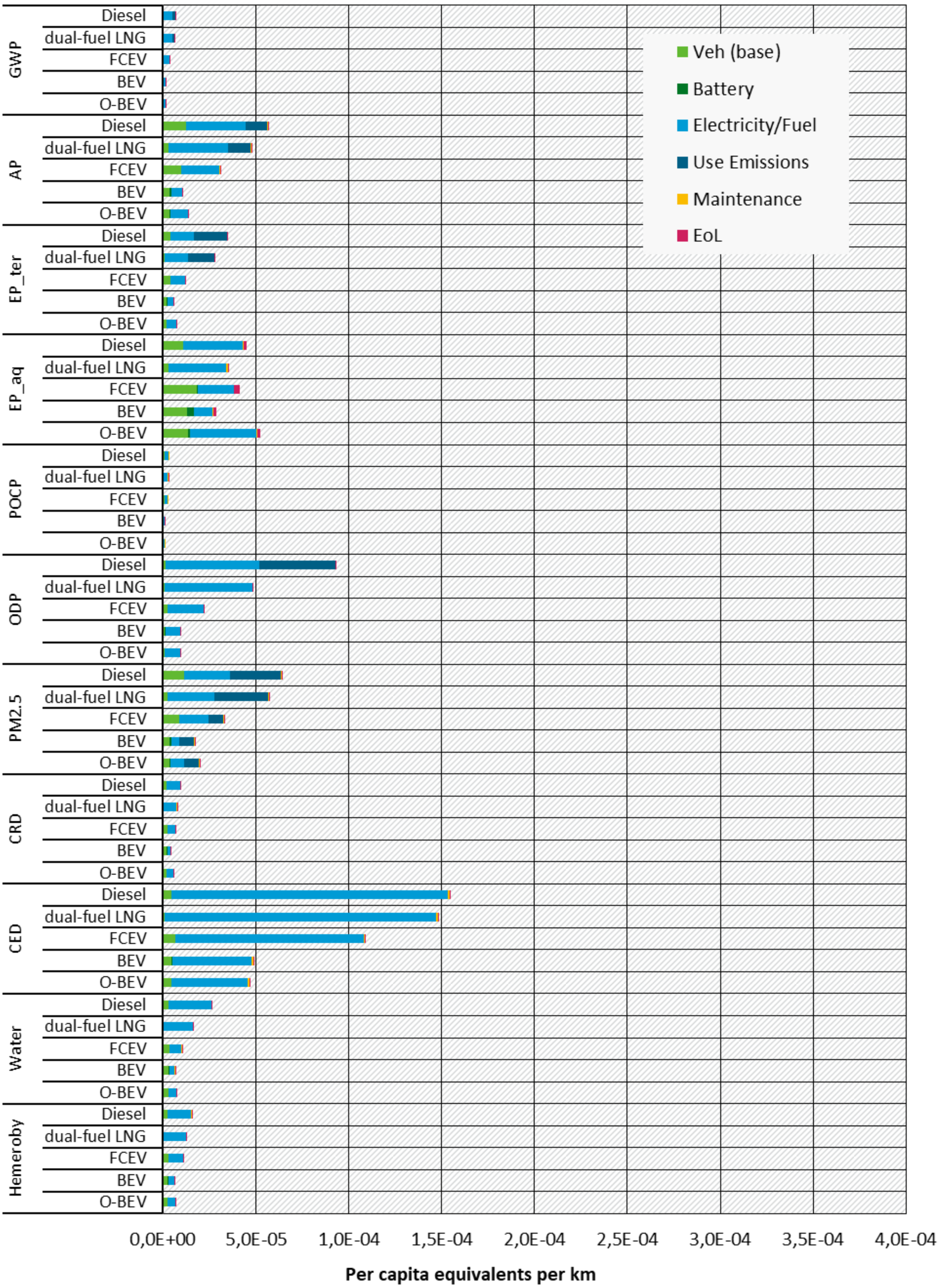
The year 2030 is chosen here for the evaluation, as all alternative powertrain concepts will be available at that time. The results for 2020 are not listed here. The results for the conventional drivetrains differ only slightly between 2020 and 2030 due to the slightly higher fuel demand in 2020.

In general, diesel vehicles and those with dual-fuel LNG propulsion are close to each other in most categories - with slight disadvantages for diesel in global warming potential, acidification, terrestrial eutrophication, photochemical ozone formation and particulate matter formation. The same applies to cumulative energy demand and hemeroby. For ozone depletion, impacts for diesel vehicles are more than six times higher than those with dual-fuel LNG propulsion due to their N_2O emissions.

The results for BEVs and O-BEV trucks are significantly lower than those of diesel and dual-fuel LNG vehicles in the categories global warming potential, terrestrial eutrophication, photochemical ozone creation, cumulative energy demand and freshwater. In the categories acidification, particulate matter formation, cumulative raw material demand and hemeroby, these two drivetrains perform roughly the same. The ozone depletion potential of electric heavy-duty vehicles is higher than that of dual-fuel LNG, but lower than that of diesel trucks. In aquatic eutrophication, BEVs and O-BEVs show values which are around three times higher than for all other powertrain types. This is due to the fossil share in the grid electricity used, where leaching from coal mining dominates this category.

In many categories, heavy-duty vehicles with fuel cells lie between conventional and electric vehicles. For acidification, terrestrial eutrophication, ozone depletion potential, particulate matter formation and hemeroby, FCEV trucks are even the best option.

Figure 15: Normalised results of all examined environmental and resource categories for heavy-duty trucks with 11t payload (year of manufacture 2050, GreenSupreme)



Source: own calculations ifeu

Figure 15 shows the normalised results of all examined impact categories for heavy-duty vehicles with year of manufacture 2050 and average electricity and fuel mixes according to the GreenSupreme scenario.

Compared to 2020, total impacts decrease in almost all impact categories, especially in the important categories acidification, aquatic eutrophication and particulate matter formation, which, however, remains the categories with the greatest impact. The global warming potential is also no longer the leading category for heavy-duty vehicle. An increase can be observed for diesel and dual-fuel LNG vehicles in the ozone depletion category. This is due to the N_2O emissions from exhaust gas denitrification and the provision of electricity-based fuels. In contrast to passenger cars, direct use emissions for the diesel and dual-fuel LNG vehicle play a greater role in acidification and terrestrial eutrophication. For all drivetrains, the contribution of tyre wear to particulate matter formation is still significant in 2050. Vehicle and fuel production dominate all other impact categories. The exception is aquatic eutrophication, where for the overhead-catenary truck the wear and renewal of the contact wire due to copper production provides significant impacts.

There are significantly greater differences between the powertrain concepts for heavy-duty vehicles built in 2050 than for passenger cars and light commercial vehicles. Fuel supply and direct emissions provide four to five times higher impacts for diesel and dual-fuel LNG in the categories acidification and terrestrial eutrophication compared to (O-)BEV vehicles. In a direct comparison, particulate matter formation is three times higher. In the ozone depletion category, internal combustion engine vehicles also have higher impacts. FCEV vehicles occupy a middle position in this comparison. Only in aquatic eutrophication is the picture more balanced. Here, O-BEV vehicles show the worst result.

The resource categories raw material demand, cumulative energy demand, freshwater demand and hemeroby reflect the electricity required to produce the fuels. Hydrocarbons are therefore associated with higher loads than hydrogen or the direct use of electricity.

4 Conclusion and outlook

An accelerated transition to alternative powertrains and fuels is urgently needed in the coming years to meet both the interim target of approximately halving greenhouse gas emissions from transport by 2030 compared to 1990 and the long-term target of near greenhouse gas neutrality by 2050. Very different combinations of powertrains and fuels are under discussion. This study therefore provides a comprehensive assessment of the environmental impacts of the different options over their entire life cycle. The results make it possible to compare different powertrain options at different points in time for a wide range of impact categories.

Table 10 and Table 11 show, for the impact categories with a particularly relevant contribution (see Chapter 3.2), the deviations from today's dominant reference technology (petrol cars and diesel heavy-duty vehicles) with the same year of manufacture with a colour coding. The year 2050 represents a decarbonised world. This affects both the energy supply for the use phase and the material supply chains. The reference technology of the internal combustion engine will then be powered exclusively by renewable synthetic fuels. The environmental impact will already be at a very low level (see section 2.2).

Table 10 : Deviations of selected environmental impacts of compact class passenger cars per vehicle kilometre compared to the petrol-powered vehicle of the same year of manufacture (2020 and 2030 GreenLate, 2050 GreenSupreme)

Year of manufacture	Impact category	Petrol (comparison to petrol 2020 as reference value)	Diesel	FCEV	BEV	PHEV
2020	GWP	0%	1%	-16%	-41%	-20%
	KEA	0%	4%	-12%	-23%	-12%
	AP	0%	5%	70%	25%	10%
	EP_aq	0%	20%	60%	221%	96%
	PM2.5	0%	10%	60%	23%	13%
2030	GWP	-11%	3%	-12%	-48%	-30%
	KEA	-8%	4%	-9%	-21%	-14%
	AP	0%	6%	10%	11%	-5%
	EP_aq	+11%	8%	23%	78%	28%
	PM2.5	+2%	9%	8%	8%	0%
2050	GWP	-96%	23%	-34%	-67%	-38%
	KEA	+56%	-7%	-41%	-67%	-38%
	AP	-36%	9%	8%	-66%	-29%
	EP_aq	-47%	-6%	0%	-27%	-18%
	PM2.5	-44%	13%	6%	-58%	-17%

light green/ocker = slight advantages or disadvantages (> +/- 10 %) ;
dark green/ocker = significant advantages or disadvantages (> +/- 40 %)
grey = similar load (< +/- 10 %))
Source: own calculations ifeu

For passenger cars (Table 10), the following conclusions arise:

- The rating of the diesel car is broadly comparable to that of the petrol car in almost all years of production. However, in terms of global warming potential, diesel cars have a slight disadvantage compared to petrol cars due to higher N_2O emissions in 2050. At the same time, petrol and diesel cars built in 2050 have significant disadvantages compared to the other technologies, as decarbonisation via synthetic fuels is associated with high conversion losses. Nevertheless, due to the assumed decarbonisation, the global warming potential in 2050 is already at a very low level (on average -96% compared to 2020).
- In the medium term (up to 2030), FCEVs have only a small advantage over internal combustion vehicles in terms of GWP and KEA. Even by model year 2050, the advantage remains well below that of BEVs. The balance for the other environmental impacts (acidification, eutrophication and particulate matter) is still clearly negative, but will improve in the medium and long term, mainly due to a reduction in the platinum load of the

fuel cell. The balance for environmental impacts beyond GWP and KEA then converges with the internal combustion engine reference technologies.

- The BEV has the lowest global warming potential over all years of manufacture and also has the lowest CED. The BEV has clear disadvantages in the other impact categories, especially in the short term (year of manufacture 2020) for aquatic eutrophication. This is largely due to the contribution of coal-fired electricity in the German grid mix. Although these effects decrease significantly by the year of manufacture 2030, they are still relevant. Only in a decarbonised world will the BEV have advantages over the other technologies in all relevant impact categories: In almost all relevant impact categories (except aquatic eutrophication), the environmental impacts are then only one third of those of petrol cars.
- As expected, the PHEV scores between the petrol and BEV in all areas. Although the negative impacts on AP, EP_ter and PM2.5 are limited due to the smaller batteries, the global warming potential is significantly higher than for the BEV due to the internal combustion engine. This is even the case if fully renewable synthetic fuels are used with a year of manufacture of 2050.

Table 11 : Deviations of selected environmental impacts of heavy-duty vehicles per vehicle kilometre compared to the diesel-powered trucks of the same year of manufacture (2030 GreenLate, 2050 GreenSupreme)

Year of manufacture	Impact category	Diesel (comparison to diesel 2020 as reference value)	Dual-fuel LNG	FCEV	BEV	O-BEV
2030	GWP	0%	-6%	2%	-55%	-60%
	KEA	0%	-1%	5%	-22%	-31%
	AP	0%	-17%	-36%	3%	-23%
	EP_aq	0%	20%	9%	221%	197%
	PM2.5	0%	-10%	-33%	-10%	-29%
2050	GWP	-94%	-6%	-47%	-76%	-77%
	KEA	+71%	-4%	-30%	-69%	-70%
	AP	-17%	-16%	-46%	-82%	-76%
	EP_aq	-52%	-22%	-9%	-36%	16%
	PM2.5	-29%	-10%	-49%	-73%	-69%

light green/ocker = slight advantages or disadvantages (> +/- 10 %);
dark green/ocker = significant advantages or disadvantages (> +/- 40 %)
grey = similar load (< +/- 10 %))
Source: own calculations ifeu

For heavy duty vehicles, the full range of alternative powertrain technologies is not expected to be available until the year of manufacture 2030. The differences compared to diesel heavy-duty vehicles of the same year of manufacture (Table 11) show:

- In the medium and long term, there are only minor advantages for the dual-fuel LNG truck in terms of GWP and KEA compared to the diesel reference. The advantages and disadvantages for the other environmental impacts are also limited. The higher impact for aquatic eutrophication for the year of manufacture 2030 is mainly due to the use of coal-based grid electricity for liquefaction at the filling station.
- In the medium term (year of manufacture 2030), fuel cell heavy-duty trucks also have no advantage over the diesel reference in terms of GWP and KEA. This is due to the use of fossil natural gas to produce hydrogen. Only in a decarbonised world will the FCEV also have clear advantages in GWP and KEA compared to the diesel reference, but these will still be well below those of BEVs and O-BEVs.
- BEV trucks already have a significantly lower global warming potential in the medium term. In the year of manufacture, 2030, it is already less than half that of the diesel reference. The advantages in terms of KEA are also clear in the medium term. On the other hand, there are still major disadvantages in terms of aquatic eutrophication due to the large battery and the remaining share of coal-fired electricity in the grid mix, which can only be largely avoided in the long term (2050) with global decarbonisation.
- Trucks with traction battery and dynamic charging (O-BEV) have a similar GWP and KEA balance to the BEV, but avoid or reduce the negative environmental impacts of the BEV in other areas already in the medium term. Only aquatic eutrophication remains negative compared to the diesel reference due to copper production, wear and replacement of the contact wire.

Overall, the battery electric vehicle concepts for both passenger cars and heavy-duty vehicles are consistently superior in terms of GWP and CED, but still have significant negative impacts in the medium term in terms of other relevant environmental impacts, in particular aquatic eutrophication. In a decarbonised world (2050), all technologies are at a lower level in terms of environmental impact, but most environmental categories do not decrease as much as GWP. While the GWP per vehicle kilometre for passenger cars is reduced by 96% on average compared to 2020, acidification and particulate matter are reduced by only 40-60%. These environmental impacts also show clear advantages for BEVs compared to the other powertrains.

The key drivers of the development towards a low environmental impact are the scenario assumptions on the decarbonisation of the electricity supply in Germany and, in the long term, the import of renewable synthetic fuels and the decarbonisation of the global energy and production system. On the one hand, it is important to avoid the negative impacts associated with alternative propulsion systems in the future, especially in terms of aquatic eutrophication. These are mainly related to the production of copper, steel, platinum group metals and aluminium for the vehicles and the share of coal-fired electricity in the grid mix.

On the other hand, reducing greenhouse gas emissions from transport remains the key challenge and is also subject to medium- and long-term targets. Important levers for improvement have been identified:

1. Especially for passenger cars, **energy efficiency** remains an important factor. Analysis of the range of fuel consumption on the market shows a clear potential for improvement in GWP over the entire life cycle, as fuels and traction electricity is still generated with significant fossil shares in the medium term. In the case of PHEVs, increasing the share of electric driving can also significantly improve the GWP balance in the short term. For heavy-duty vehicles, the data show a trend towards a narrower range of fuel consumption due to cost pressure.

2. **Energy supply** is the central issue of the GWP balance in the medium and long term, whereby the individual vehicle user has only a few options to individually use additional renewable energy. It is therefore all the more important that the ambitious expansion of renewable energy is continued in order to realise at least the path of decarbonisation of electricity supply in Germany taken as the standard case (GreenLate) or to accelerate it even further if possible (GreenSupreme). In contrast, a targeted use of additional renewable energies for charging electric vehicles is hardly possible within the current energy-economic framework in Germany.
   For combustion and fuel cell vehicles, the balance for the year of manufacture 2030 can only be improved by a higher share of renewable imported fuels to close the gap to the development in the electricity sector. However, very high shares (> 70 %) of renewable fuels would then be necessary to achieve a GWP balance comparable to BEVs. The associated challenges are considerable.
   In the case of imports of gaseous synthetic fuels, import via pipelines is also clearly preferable to liquefied transport from the perspective of climate impact. The same applies to distribution in Germany. If synthetic natural gas or electrolytic hydrogen is transported by ship, liquefaction should at least be carried out with renewable energies. Liquefaction with partly fossil grid electricity worsens the environmental balance considerably. The same applies to compression or liquefaction at the filling station. Here, too, operation with grid electricity is still associated with significant disadvantages in the medium term.
3. **Optimising the production of powertrain components** has an impact on the global warming potential over the entire life cycle and in particular on the differences between technologies. The focus should lie on limiting battery sizes to reduce all processes associated with cell production and the EoL of the cells. However, improvements in energy density and cell production with predominantly renewable electricity can also improve the GHG balance. In the case of FCEVs, this is achieved by reducing the platinum load of the fuel cell. However, over the life cycle of the vehicle, the impact on the GWP is limited as the GWP is currently dominated by the hydrogen provision. Significant improvements can be achieved through these measures.
4. Finally, **closed raw material cycles and extended service life**, especially of the vehicle battery, contribute to an improved overall balance. A flexible and optimised recycling system reduces the environmental impact and can at least reduce the demand for primary raw materials.

In terms of climate protection, the study largely confirms the market trend towards the predominant use of battery-electric powertrains in the transport sector. At the same time, however, there are still significant negative effects on other relevant environmental impacts, especially in the short term. These are mainly related to the production of the powertrain components (batteries, fuel cells) and partly to their infrastructure (wear and maintenance of overhead lines), as well as to the remaining share of coal-fired electricity. In addition to an early phase-out of coal, supply chains and production processes should be improved.

It is true that fuel cells and synthetic fuels also have the potential to significantly improve the GHG impact of vehicles in largely decarbonised energy chains. However, in view of the expected high demand in other sectors, the challenges of developing the relevant energy markets in such a way that road transport is supplied with largely GHG-neutral energy sources at an acceptable cost are enormous. Compared to the decarbonisation of the national electricity supply, from which battery electric vehicles directly benefit, a significant delay and corresponding negative impact on the cumulative GHG emissions from transport by 2050 can be expected.

Even in a decarbonised world, BEVs will continue to have environmental advantages over other powertrains in all relevant impact categories. In the case of renewable fuels, it is also important to ensure that, in addition to the economically and technically challenging technology ramp-up, sustainability criteria are met in terms of political, social and environmental requirements. In particular, the potential for direct use of renewable electricity in the producing countries must be exploited before the electricity is converted into PTL or hydrogen with energy losses. Detailed criteria for this are being developed in the UBA project "Criteria for the sustainable supply and climate-friendly integration of electricity-based renewable energy sources"

In general, the results of this study are based on robust assumptions. However, there are some methodological issues that should be addressed in subsequent research projects:

- In the future, especially in dynamic areas such as traction batteries, it will be important to include new developments (e.g., production processes, cell chemistries, energy densities) and to improve, update or verify previous assessments.
- The data on synthetic hydrocarbon production is largely based on engineering modelling from the technical literature or from the research we have carried out. Primary data from the first commercial plants under construction would be valuable to verify these models. Lower efficiencies, e.g., due to less ambitious heat integration, and higher direct emissions could worsen the balance of synthetic fuels.
- In this study, upstream fossil fuel emissions have been calculated excluding enhanced methane emissions, which are now included in United Nations environmental targets and major life cycle assessment databases. This should be considered when communicating the results. Future research projects should take these environmental impacts into account.
- The GreenLate and GreenSupreme scenarios, on which this study is based in several places, also need to be compared with real developments. On the one hand, they were originally designed with a starting date of 2015 and should be updated. On the other hand, these scenarios assume a similar - albeit phased - decarbonisation across the world. Since German and European environmental policies have only limited influence on regulations outside their jurisdiction, it is necessary to examine the consequences of a much delayed or incomplete phase-out outside Europe for the environmental performance of vehicles and fuels.

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