WWW.FRONTIER-ECONOMICS.COM

NEED FOR A LIFE-CYCLE ASSESSMENT IN FLEET EMISSION TARGETS

A study conducted on behalf of UNITI Bundesverband mittelständischer Mineralölunternehmen e.V. (German association of small and medium-sized mineral oil companies)

04 AUGUST 2023

English translation of the original German study

DR. JENS PERNER
THERESA STEINFORT
MARION LOTHMANN

Contents

frontier economics

frontier economics

SUMMARY

The CO_2 emission standards for new passenger cars and for new light commercial vehicles (Regulation (EU) 2019/631, referred to in the following as “fleet emission targets”) are designed to reduce greenhouse gas emissions in the EU.[1]

The previous regulation as well as the regulation that recently came into force (2023/851) adopt a “tank-to-wheel” approach (TTW), which only considers one portion of the CO_2 emissions (“tailpipe emissions”) generated over the entire life cycle of a vehicle.

With a TTW approach, electric vehicles always appear to be emission-free, while internal combustion engine vehicles cause CO_2 emissions continuously. The fleet emission targets do not distinguish between fuels with CO_2-reduced or CO_2-neutral production, e.g. biofuels such as Hydrotreated Vegetable Oil (HVO) produced from leftover/waste materials or fuels produced from renewable electricity such as e-fuels etc.

In contrast to the TTW approach, life-cycle assessments (referred to in the following as LCA) include also other significant emission categories from road vehicles, in particular:

(a) **Vehicle production (“cradle-to-gate”)**: This includes all CO_2 emissions generated during production of the components of the different drive systems and the body, as well as other vehicle components such as the vehicle equipment (including batteries on battery electric vehicles).

(b) **Energy supply (“well-to-tank”)**: CO_2 emissions associated with the supply of the required fuel or electricity for charging, including upstream chains.

(c) **Provision of infrastructure**: Depending on the type of technology and/or fuel, additional infrastructure may be required (e.g. charging station infrastructure, construction of synthesis capacities for the production of synthetic liquid fuels etc.)

(d) **Vehicle use (“tank-to-wheel”)**: This includes all CO_2 emissions generated during the use of the vehicle, primarily the so-called tailpipe emissions.

(e) **Disposal and/or recycling (“end-of-life”)**: End-of-life vehicle disposal and/or disassembly or recycling may also in some cases generate CO_2 emissions (including e.g. due to the use of electricity that is not generated 100% from renewable energy sources).

If an LCA approach is pursued, it becomes evident that no single drive technology has a clear advantage in terms of CO_2 emissions and the potential for reducing CO_2 emissions. This is different if a TTW approach is applied. When pursuing an LCA approach, the climate

[1] Refer to Regulation (EU) 2019/631, https://eur-lex.europa.eu/legal-content/DE/TXT/HTML/?uri=CELEX:32019R0631#d1e1329-13-1

impact of individual drive technologies and vehicles depends on a large number of factors, including e.g. the carbon intensity of the underlying electricity mix as the source of energy for battery electric vehicles, the CO_2 emissions generated during the production of vehicle components (in particular in battery production), the share of CO_2 neutral fuels used in internal combustion engines etc.

The calculation of total CO_2 emissions across the life cycle thus need to be looked at on a case-by-case basis, both for battery electric vehicles and for internal combustion engine vehicles. Accordingly, the advantageousness of a particular drive technology in terms of climate impact also depends on the individual scenario.

Depending on the particular case, a vehicle with battery electric drive or with an internal combustion engine can therefore either prove advantageous in terms of CO_2 life-cycle emissions. By contrast, a TTW approach suggests that battery electric vehicles would generally offer an advantage. Therefore, from a climate perspective, this approach is not appropriate. Required are approaches based on life-cycle analyses.

In addition, a wider shift towards life-cycle assessments for determining the CO_2 emissions of products and technologies is happening both in technical literature and in climate policy regulations.

Applying a TTW approach in the regulation of individual sectors involves the risk of distortion and disincentives. This can potentially run counter to the objectives of climate protection.

(a) When using a TTW approach, the players involved may choose technologies that can potentially, overall, lead to higher CO_2 emissions. This goes against climate protection. The extent to which climate protection is countered rather than pursued depends on a large number of factors, but particularly on the interaction between the incentives and support schemes for the relevant technologies that aim to lower CO_2 emissions at different stages of the value chain.

(b) CO_2 emissions generated outside of the EU are systematically not accounted for in a TTW approach. Although this makes it easier to meet climate targets within the EU, it weakens climate protection at a global level. Political and regulatory measures that can have a corrective effect here, such as the Carbon Border Adjustment Measures (CBAM), are not yet effective at present, and the way in which these measures will be shaped in the future is at least still up for debate.

Overall, choosing an LCA approach to determine CO_2 emissions of products and technologies is therefore consistent with the scientific state-of-the-art and is to be classified as appropriate to evaluate the climate impact.

1 Mandate and structure of the study

The CO_2 emission standards for new passenger cars and for new light commercial vehicles (Regulation (EU) 2019/631, referred to in the following as “fleet emission targets”) are designed to reduce greenhouse gas emissions in the EU.[2] Here, the current regulation adopts a “tank-to-wheel” approach (TTW), which only considers a portion of the actual CO_2 emissions (“tailpipe emissions”) generated over the entire life cycle of a vehicle.

On behalf of *UNITI Bundesverband mittelständischer Mineralölunternehmen e. V.* (German association of small and medium-sized mineral oil companies), Frontier Economics developed a model for calculating CO_2 emissions for passenger cars in 2019.[3] This model can be used to calculate the emissions of battery electric vehicles (BEV) and internal combustion engine vehicles (ICEV) in various manufacturing and use scenarios.

Against this background, *UNITI Bundesverband mittelständischer Mineralölunternehmen e. V.* has commissioned Frontier Economics to compare and illustrate various approaches for determining the climate footprint of different drive types – firstly the TTW assessment and secondly the life-cycle assessment (LCA). Key assumptions and data from the 2019 model calculations have been selectively updated.

The short study covers the following main focal points:

- Section 2 illuminates the background of the fleet emission targets,
- Section 3 compares the methodological approaches for the calculation of CO_2 emissions that focuses on tailpipe emissions (“tank-to-wheel”, TTW), which is the method underlying the fleet emission targets, against the calculation of CO_2 emissions across the entire life cycle.
- Section 4 illustrates the results for CO_2 calculations obtained firstly via the TTW approach and secondly via the life-cycle based on an example vehicle and a sample model of vehicle use.
- In section 5 it is shown that the life-cycle approach is increasingly becoming established both in technical literature and in climate protection regulations.
- In section 6 we address the risks associated with the use of a TTW approach and the consequences for climate protection.
- Section 7 contains the conclusion.

2 Refer to Regulation (EU) 2019/631, https://eur-lex.europa.eu/legal-content/DE/TXT/HTML/?uri=CELEX:32019R0631#d1e1329-13-1, article 1(1).

3 See Frontier Economics (2019).

2 Fleet emission targets define emission reduction targets for new vehicles in order to reduce CO_2 emissions in the transport sector

Since 2009, passenger cars and light commercial vehicles have been subject to the regulation of emission standards in the European Union. The underlying idea is that all manufacturers are being required to reduce the Europe-wide average CO_2 emissions of their new vehicles to below an increasingly restrictive annual fleet threshold value or face comparatively high penalties (currently around €450-600 per tonne of CO_2, see Table 1) if the fleet targets are exceeded.

In this regulation, requirements are placed on the CO_2 emission performance of new passenger cars and new light commercial vehicles in order to help attain the objectives targeted by the European Union for a reduction in greenhouse gas emissions as defined in Regulation (EU) 2018/842 and to achieve the objectives of the Paris Convention, and to ensure the effective functioning of the internal market.[4]

Regulation (EU) 2019/631 came into force on 1 January 2020; it defines CO2 emission standards for new passenger cars and light commercial vehicles (LCV). It replaced and superseded the previous Regulation (EC) 443/2009 (passenger cars) and Regulation (EU) 510/2011 (light commercial vehicles).

On 25 April 2023 the new Regulation (EU) 2023/851[5] amending Regulation (EU) 2019/631 came into force in order to strengthen the CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the European Union's increased climate ambitions (as part of the "Fit for 55" package)[6]. With this adjustments, the emission goals that apply from 2030 are particularly intensified and a 100% reduction goal from 2035 onward is put into place. The TTW approach – i.e. a sole focus on tailpipe emissions – was retained, which means that from 2035 a de-facto ban on the registration of new internal combustion engines vehicles will come into force and only electric vehicles will be able to satisfy the zero emissions requirements.[7]

Table 1 summarises the key points:

4 See article 1(1) of Regulation (EU) 2019/631.

5 Regulation (EU) 2023/851, https://eur-lex.europa.eu/legal-content/DE/TXT/HTML/?uri=CELEX:32023R0851&qid=1688743351340

6 See European Commission (2021a).

7 Internal combustion engines can also be powered by hydrogen. Since hydrogen does not contain carbon, no pollutants containing carbon are released through the exhaust gas. However, in practice this drive type is not currently relevant in the transport sector.

Table 1 Key points for fleet emission targets (date: June 2023)

Addressee	Vehicle manufacturer [8] (OEM)
Reference value	New registrations of passenger cars and light commercial vehicles in the EU within a calendar year
Target value	■ Fleet average of **tank-to-wheel emissions (tailpipe emissions)** measured in grams of CO_2 per km of driven distance ("g/km") (see **section 3** for further explanations) ■ From 2021, emissions per new vehicle and the target values are determined via the WLTP method (Worldwide Harmonized Light Vehicles Test Procedure).
Emission targets	■ 2020 target (starting value in NEDC[9]) • Passenger cars: 95 g/km • Light commercial vehicles: 147 g/km ■ Target path (in comparison to 2021): • Passenger cars: -15% from 2025, -55% from 2030, -100% from 2035 • Light commercial vehicles: -15% from 2025, -50% from 2030, -100% from 2035
OEM-specific target adjustment	Based on the average weight in the vehicle fleet (i.e. the heavier the weight, the higher the individual target value)
Penalty payments if limit is exceeded	If the fleet targets of an OEM are exceeded then the OEM must pay a penalty of €95 per g/km of target exceedance (~€450-600 / t CO_2[10]) for each of its vehicles newly registered
Other rulings	■ OEMs can group together in a CO_2 pool and act jointly to meet their emissions target (limited to a maximum of 5 years). ■ Due to the efforts of the German Federal Government, recital 11 was integrated in the regulation. The wording of this

8 Exceptions apply to manufacturers that account for fewer than 300,000 registered vehicles per year, and there is an exemption for manufacturers with fewer than 1,000 vehicles. These exceptions will no longer apply after 2028.

9 In 2020 the target values were determined via the NEDC test method, which was applicable at the time, but this has now been replaced by the WLTP method.

10 €95/g/km divided by an average lifetime mileage of 160,000 - 200,000 km, multiplied by a factor of 10^6 (g/t). The assumption of a longer mileage would lead to a lower CO_2 price and vice versa.

is as follows: "Following a consultation with stakeholders, the Commission will make a proposal for registering vehicles running exclusively on CO2-neutral fuels, after 2035, in conformity with EU law, outside the scope of the fleet standards, and in conformity with the EU's climate neutrality objective."[11] However, this amendment is still to be developed by the Commission. It is currently still unclear whether and when an implementation is to take place. The responsible Commissioner Frans Timmermanns has announced this but not yet submitted a draft[12]. The recital itself offers no legal certainty here. In this matter, the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) declared: "In contrast to the legal norms themselves, no immediate legal consequences can be derived from the recital, and instead it is merely declarative."[13]

- In addition, the relevance of using life-cycle analyses in the determination of greenhouse gas emissions of conventional vehicles and vehicles powered with alternative drive systems follows directly from the fleet emission targets themselves. Here, in the regulations that define CO_2 emission standards for passenger cars, light commercial vehicles[14] and for heavy goods vehicles[15], there are provisions that the emissions of such vehicles that are registered in the European Union must be assessed across the entire life cycle. In order to do this, by 2023 the Commission was to explore the possibility of developing a corresponding methodology and presenting suitable follow-up measures and, if applicable, legislative proposals.[16] However, based on Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles[17], these objectives

11 Regulation (EU) 2023/851 https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32023R0851

12 See BMUV (2023).

13 See BMUV (2023).

14 Regulation (EU) 2019/631, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631.

15 Regulation (EU) 2019/1242, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1242&qid=1689162171924

16 Regulation (EU) 2019/631 and 2019/1242, section 15(2).

17 Regulation (EU) 2023/851 https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32023R0851

	have been pushed back. According to the newly introduced Article 7a, the Commission will publish by 31 December 2025 a method description for determining the CO_2 emissions across the entire life cycle. However, the two following reasons stand against the idea that this Article 7a will be able to deliver concrete relevance in connection to the fleet CO_2 target values: i) Article 7a (1) and (2) only contains the description and definition of a shared European Union method for reporting (i.e. publishing) the CO_2 emissions across the life cycle. According to this, although manufacturers of drive technologies who, through a comprehensive determination of CO_2 emissions, can prove that the carbon footprint of their drive technology/technologies is more advantageous than with a sole TTW approach will have a general interest in making this information available, this information does not, however have obvious relevance for the methodology used to determine the limit values. It is therefore not evident how this Article will contribute to ensuring that the CO_2 emissions attributed to mobility are appropriately considered. Ii) Moreover, communication of the corresponding data is voluntary for the manufacturers (see section 3(7)(a) of the above regulation). It is unclear to what extent manufacturers will exercise this voluntary option.

Source: Frontier Economics based on the consolidated version https://eur-lex.europa.eu/legal-content/DE/TXT/HTML/?uri=CELEX:02019R0631-20230515#tocId7

3 In the “tank-to-wheel” (TTW) approach, the fleet emission targets only consider a portion of the life-cycle emissions

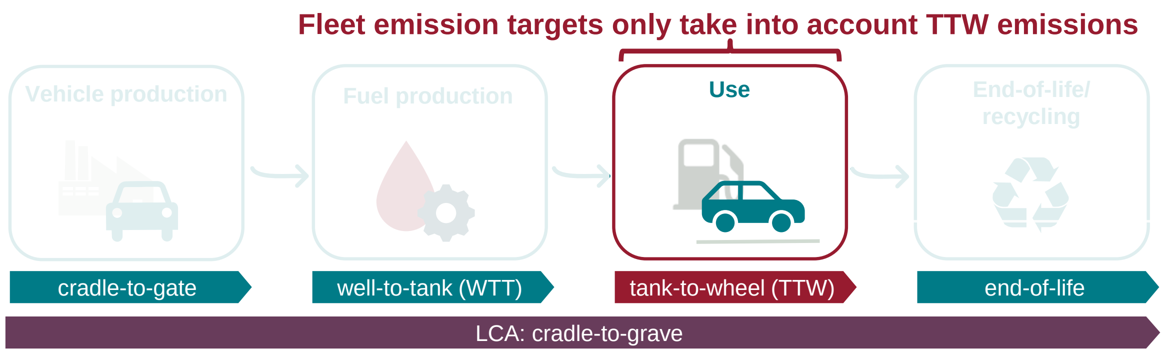
In this section we demonstrate that the “TTW” approach used in the fleet emission targets:

- only takes into account CO_2 emissions generated directly during use (at the tailpipe of the vehicle) (section 3.1); and
- as a result, a large proportion of the CO_2 emissions in the life cycle of a vehicle is ignored (section 3.2).

3.1 The “TTW” approach only considers CO_2 emissions generated directly during the actual use (at the tailpipe)

The fleet emission targets focus on the tank-to-wheel CO_2 emissions of the vehicle itself, the so-called tailpipe emissions. These emissions are generated during the actual use of the vehicle.

Figure 1 TTW approach only includes CO_2 emissions generated during use of a vehicle



Source: Frontier Economics

Using the TTW approach (i.e. a focus on tailpipe emissions) has the following consequences for the fleet emission targets:

(a) The CO_2 emissions from electric[18] vehicles are assigned a value of zero across the board, as these vehicles do not have an exhaust system, regardless of the CO_2

18 This includes battery electric vehicles and vehicles with fuel cells in which hydrogen is converted to electricity.

emissions generated during vehicle manufacture (incl. battery), electricity or hydrogen generation and end-of-life disposal or recycling.

(b) By contrast, CO_2 emissions from vehicles with internal combustion engines are always positive and depend only on the fuel consumption of the relevant vehicle model (measured based on the model-specific criteria "Worldwide Harmonised Light-Duty Vehicles Test Procedure" (WLTP) – value 2), regardless of e.g. whether:

(i) components used in the manufacture of the vehicle are produced using fossil or renewable energy; such as metal components made of "green steel" or "green aluminium", or non-metallic components (plastics) manufactured in a climate-friendly manner;

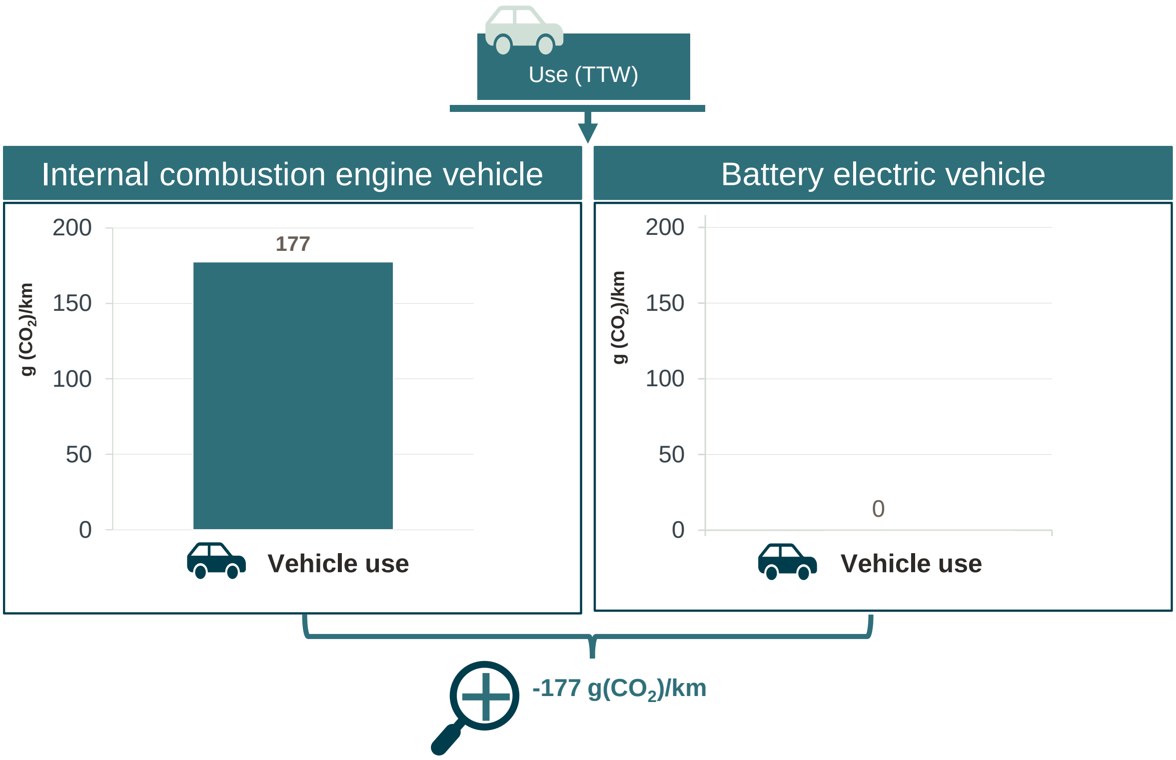
(ii) the vehicle is fuelled with carbon-neutral fuels. Here and in the following, the term "carbon-neutral fuels" is used to describe both biofuels, such as biomass from leftover/waste materials (e.g. Hydrotreated Vegetable Oil (HVO) produced from used cooking oil), as well as fuels produced from renewable electricity (e-fuels).[19]

Figure 2 provides an illustration of this using a comparison between a battery electric vehicle with supposed "zero emissions" (right) and an internal combustion engine vehicle (left), which has a positive TTW CO_2 value.

---

19 In the established literature that deals with the effects of greenhouse gases on global warming, the terms "greenhouse gases" and "CO_2 equivalents" are typically used synonymously, and for simplicity these are also shortened to just "CO_2 emissions". In accordance with the fleet emission targets, which also refer specifically to CO_2 emissions, this is the expression we have also used synonymously in this short study. Furthermore, when CO_2 emissions are calculated comprehensively, there is a certain ambiguity about applying the term CO_2-*neutral*. This depends on where the system limits for each CO_2 calculation are drawn (e.g. exactly which CO_2 burden is taken into account in the construction of (additional) wind power plants). Explanations about this can be found, among others, in the study from Frontier Economics (2020). In the following, despite the remaining indirect CO_2 emissions from upstream chains (depending on the system limits) we use the term CO_2-neutral, but we also take into account the CO_2 footprint of the upstream chain emissions from the construction of renewable energy facilities or other residual emissions in the calculations. Consequently, even if "CO_2-neutral" fuel is used exclusively or the electricity for charging is 100% generated from renewable energy sources, this will still not reduce the well-to-wheel emissions to zero if there are emissions upstream in the chain.

Figure 2 Illustrative comparison of CO_2 emissions based on the TTW approach for an exemplary vehicle for each a battery electric vehicle and an internal combustion engine vehicle powered with fossil fuels



Source: Illustration from Frontier Economics (2019), update to the assumptions and data in July 2023

Note: Vehicle type: medium-sized car; year of purchase: 2022; operating lifetime of vehicle: 10 years; annual mileage: 15,000 km; fuel: petrol (10% blending of E10); country in which the vehicle is used: Germany; manufacturing emissions for battery (e.g. in China): 140 kgCO_2/kWh of battery capacity, dynamic

3.2 The LCA approach takes into account CO_2 emissions throughout the entire life cycle and across all product stages

During the life cycle of a vehicle (see Figure 3) the following CO_2 emissions are regularly generated across the different stages of the value chain:

- **Vehicle production ("cradle-to-gate")**: This stage includes all CO_2 emissions generated during manufacturing of the components of the different drive systems and the body, as well as other vehicle components such as the vehicle equipment (including batteries for battery electric vehicles). The CO_2 emissions of the vehicle and/or component production depend on a large number of factors, including e.g. the carbon intensity of the energy or electricity mix of the country of manufacture, the technology used in the installed components, production technologies etc.

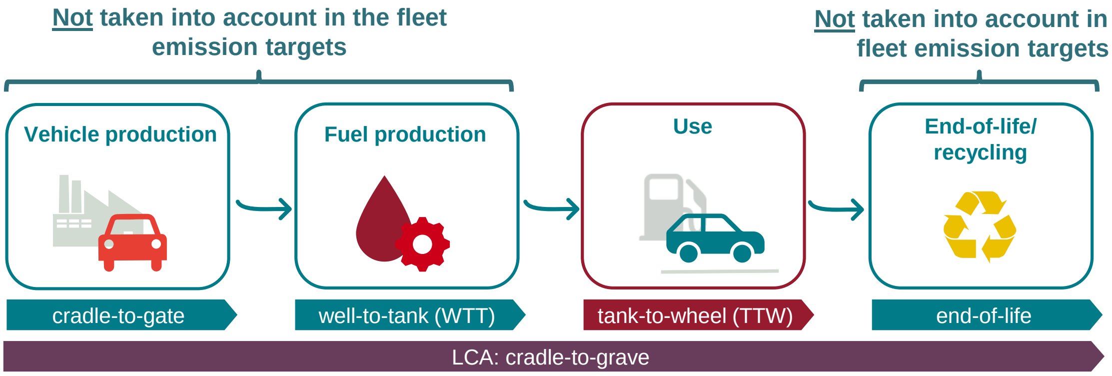
- **Energy supply ("well-to-tank")**: This includes the CO_2 emissions associated with the production and transport of the required fuel or electricity for charging, including upstream chains. The carbon intensity of the production of the fuels needs to be taken into account as well as the carbon intensity of the electricity that is available in the region in which the electric vehicle is charged. The latter will vary dynamically, in particular as a result of the increasing use of renewable energies to produce not only fuels, but also electricity for charging.

- **Provision of infrastructure**: Depending on the type of drive and/or fuel, additional infrastructure may be required (e.g. charging station infrastructure, construction of synthesis capacities for the production of synthetic liquid fuels etc.). It is generally difficult to apportion figures for the infrastructure that needs to be built up and to attribute CO_2 emissions to the individual technologies, as any infrastructure is generally used by a multitude of users. Accordingly, it is challenging to calculate proportional emission shares associated with providing the necessary (additional) infrastructure. For this reason, this stage is often omitted in LCA literature, and in the following we have likewise only offered a qualitative assessment.

- **Vehicle use ("tank-to-wheel")**: This includes all CO_2 emissions generated directly during the use of the vehicle, primarily the so-called tailpipe emissions.

- **Disposal and/or recycling ("end-of-life")**: The end-of-life phase looks at emission effects resulting from the disposal and/or recycling of the vehicle and its material component products. Through potential reuse, recovery or recycling, it is also possible that negative CO_2 contributions can be attributed to this stage and thus offset other emissions.

Figure 3 CO_2 emissions throughout the life cycle



Source: *Frontier Economics*

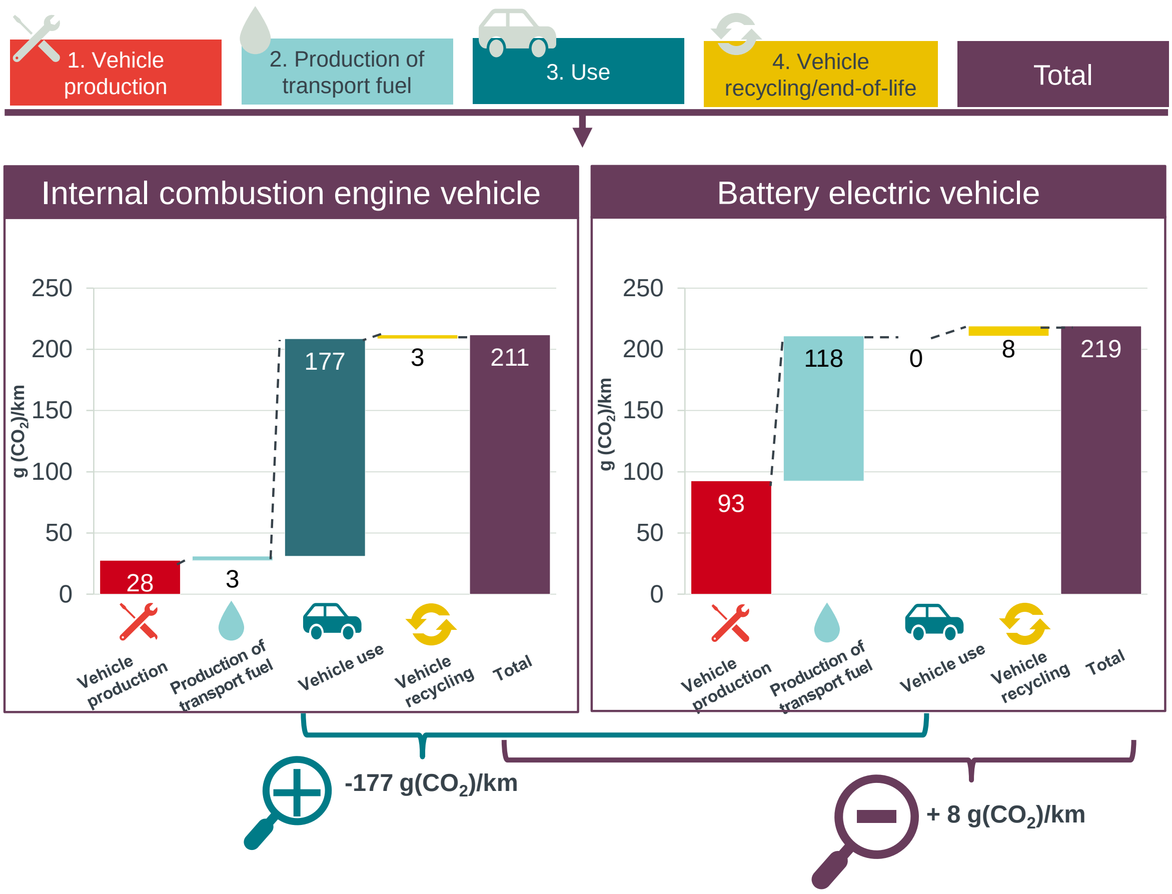
Note: *Additional CO_2 emissions for the construction and maintenance of the infrastructure are not taken into account here. For example, for battery electric vehicles further emissions incur in the market launch phase for building up the charging infrastructure.*

For this reason, the life-cycle assessment (LCA) approach has become established both in technical literature and in various regulatory areas (see section 5) for the calculation of CO_2 emissions.

As an example, Figure 4 shows the comparison of CO_2 emissions for the example vehicles[20] from Figure 2 (TTW comparison) based on the LCA approach. This shows quite clearly that the comparison between the CO_2 balances of an internal combustion engine vehicle and a battery electric vehicle changes significantly if a comprehensive approach is adopted. If only the TTW emissions are compared, as is the case in the example in Figure 2, then BEVs are at an advantage because their emissions are 177 gCO_2/km lower compared to a vehicle with an internal combustion engine. However, if an LCA approach is adopted, it can be seen that the total emissions are almost equal for both drive systems (assumption: use of a conventional fuel, e.g. E10). The relevant figures thus change substantially with the shift from a TTW approach to an LCA approach.

[20] Information about the vehicles is provided in the explanatory notes under the illustration.

Figure 4 Illustration: Contrasting life-cycle CO_2 emissions of ICEVs and BEVs (example calculation)



Source: Illustration from Frontier Economics (2019), update to the assumptions and data in July 2023

Note: Vehicle type: medium-sized car; year of purchase: 2022; operating lifetime of vehicle: 10 years; annual mileage: 15,000 km; fuel: petrol (10% blending of E10); country in which the vehicle is used: Germany; manufacturing emissions for battery (e.g. in China): 140 kgCO_2e/kWh of battery capacity, dynamic

For both drive systems – i.e. for both a battery electric vehicle and for an internal combustion engine vehicle powered with liquid fuels – CO_2 emissions will be generated for the foreseeable future in different stages of the life cycle chain. However, these differ particularly in the following phases:

(a) **Vehicle production**: CO_2 is emitted during the production of a vehicle. Here, the CO_2 emissions for a BEV are higher than for a vehicle with an internal combustion engine. More than anything else, the main driver behind the difference is the high energy demand for the production of batteries. In our illustrative example, it is assumed that battery production takes place in China – at present, around 80% of batteries for BEV worldwide come from factories in China.[21]

(b) **Production of transport fuel (WTT)**: As long as fossil energy sources contribute to the generation of the electricity used for charging, significant CO2 emissions will be associated with this product phase. By contrast, comparatively few CO_2 is emitted in the production of fossil diesel or petrol. In future, the emissions at this stage will decrease. Since the electricity mix will involve a higher share of renewable energies and other CO_2-neutral technologies, it can be assumed that the currently significant WTT CO_2 emissions for a battery electric vehicle will go down. For vehicles with an internal combustion engine that are operated with CO2-neutral fuels[22], the effect will be "negative" in terms of the carbon footprint, as these fuels are produced using natural (bio-based) or technical CO_2 sources (e.g. carbon capture technologies) and therefore act as "carbon sinks" (see point (c) below).

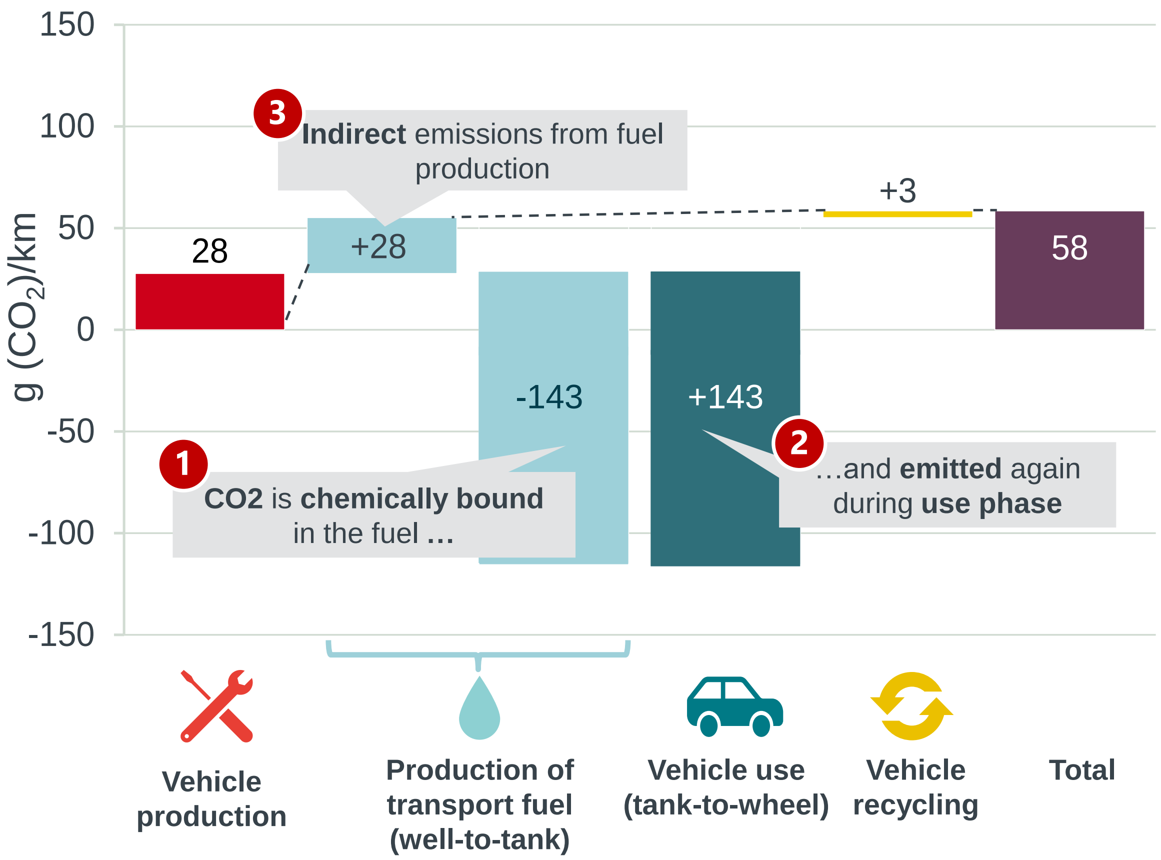
(c) **Vehicle use (TTW):** As already mentioned above, the CO2 emission balances differ particularly in the vehicle use phase. Whereas a battery electric vehicle generates zero CO_2 emissions during use, an internal combustion engine vehicle that is powered by liquid fuels will generate the majority of its CO2 emissions at this stage. Even 18anu increasing shares of CO_2-neutral fuels (biofuels, synthetic fuels from renewable electricity etc.), tailpipe CO_2 emissions will not be physically reduced.

However, as already described in (b), when calculating the carbon footprint, the removal of carbon from the atmosphere during the production of fuels offsets the emissions from the combustion (well-to-tank phase, WTT). In the case of biofuels, this CO_2 reduction in the atmosphere is down to photosynthesis processes of the plants and/or plant products processed in the fuels, while in the case of synthetic fuels from renewable electricity (e-fuels) this is due to the direct capture of CO_2 from the atmosphere (Direct Air Capture technology) or the separation of CO_2 from exhaust gases that would have otherwise made their way into the atmosphere (e.g. from industrial processes such as cement production). The climate impact of tailpipe emissions (TTW) is therefore compensated for in CO_2-neutral fuels by negative emissions during fuel production (WTT) (see Figure 5).

21 See Popien et al. (2023a).

22 Generally speaking, the assumptions underlying the calculations for the blending of CO_2-neutral fuels correspond to those that are applied in the LCA model of Frontier 2019. This approach is based on the assumption that e-fuels (as surrogates of the group of CO2-neutral fuels) are blended into fossil fuels or that e-fuels are used entirely. The blending and/or use of HVO, bioethanol or other CO_2-neutral fuels are not analysed separately in this short study. This should be regarded as a conservative approach since the emissions identified for example according to the EU WTW JEC study (see Prussi et al. (2020)) for HVO are below the (indirect) CO_2 emissions modelled by us for the production of e-fuels.

Figure 5 **Illustration: Total life-cycle CO2 emissions of an ICEV powered by CO2-neutral fuels (example calculation)**



Source: Illustration from Frontier Economics (2019), update to the assumptions and data in July 2023

Note: Vehicle type: medium-sized car; year of purchase: 2022; operating lifetime of vehicle: 10 years; annual mileage: 15,000 km; fuel: Klimadiesel90, country in which the vehicle is operated: Germany/EU, dynamic. The CO_2 emissions of the WTT and TTW stages do not offset each other entirely, as residual emissions are also incurred in the production of Klimadiesel90.

(d) However, a comprehensive approach is not only reasonable in order to compare different drive technologies with each other, but also to compare **the same drive technologies from different manufacturers** with each other (e.g. two battery electric vehicles). Assuming that there are two car manufacturers: (i) car manufacturer A produces its batteries in the EU with an electricity mix with relatively high shares of renewable energies, while (ii) car manufacturer B produces its batteries outside of the EU with an electricity mix based on a high proportion of fossil energy sources. If a comparison is takes place solely at the TTW level then both manufacturers will register zero CO_2 emissions, even though car manufacturer A is making a bigger contribution to meeting the climate protection goals. Only by looking at the LCA emission balances, we can see that there is a difference in the battery-related emissions.

As explained in section 2, according to Article 7a of Regulation (EU) 2023/851 the Commission is required to present a methodology for determining LCA emissions by the end of 2025. According to section 3 of the same article, vehicle manufacturers have the opportunity to make their LCA data available on a voluntary basis. However, this article has no impact on the objectives of the fleet emission targets as part of the TTW approach. In particular, if the requirement continues to be in place that the TTW emissions must be zero then this results in a de facto ban of vehicles with internal combustion engines. When CO_2-neutral liquid fuels are used, their climate neutrality and therefore their contribution to the climate protection goals only become evident once the negative emissions at the WTT stage are taken into account.

4 The focus on TTW emissions is distorting the assessment of the CO_2 emissions of drive technologies

When adopting an LCA approach, it becomes clear that the advantageousness of different drive technologies with regard to climate impact depends on each individual scenario. By contrast, the suggested blanket CO_2 neutrality of battery electric vehicles 22anu is implied under a TTW approach and therefore their advantageousness in terms of climate impact is not appropriate.

In this section we show that the focus on TTW emissions distorts the assessment of different drive technologies in terms of their climate impact and that it can lead to incorrect conclusions, based on:

(a) our own example calculations (section (b) 4.1); and

(b) analyses of the EU Commission created as part of the impact assessment for the revision of the fleet emission targets (section 4.2).

4.1 When applying a LCA approach it becomes evident that no clear conclusions can be drawn about the advantageousness of individual drive technologies in terms of climate impact

When adopting an LCA approach, the climate impact of individual drive technologies and vehicles depends on a large number of factors. The CO_2 emissions at the different stages in the life cycle are correspondingly dependent upon the individual scenarios and must, ultimately, be taken into account in their entirety, both for battery electric vehicles and also for vehicles with internal combustion engines.

General factors include e.g.[23] (see also Frontier Economics (2019)):

(i) size of the vehicles;
(ii) specific technical details of the vehicles, e.g. the engine efficiency;
(iii) vehicle use (mileage driven each year);
(iv) operating lifetime of a vehicle;
(v) driving behaviour;
(vi) external factors that impact energy consumption or vehicle wear-and-tear, such as outdoor temperatures, topology etc.;

23 See Frontier Economics (2019), *Die CO2-Gesamtbilanz für Antriebstechnologien im Individualverkehr heute und in Zukunft – Lebenszyklusanalysen als Basis für zielführende Klimapolitik und Regularien* (The overall CO2 impact for drive technologies in individual transport today and in the future – Life-cycle analyses as the basis for targeted climate policy and regulation).

(vii) the carbon intensity of the production of the vehicles and/or vehicle components, which depend upon the relevant production site and the technology used.

Other key driving factors for CO_2 emissions of **battery electric vehicles** include in particular:

(i) the carbon intensity of the underlying electricity mix used to generate the electricty for charging;

(ii) the carbon intensity of the battery production, which in turn depends on the chemical composition of the battery, the energy and/or electricity mix in the country of manufacture, as well as the production technologies used and the industrial scale of manufacture;

(iii) the storage capacity of the installed batteries,

A key driving factor for CO_2 emissions of **vehicles with internal combustion engines** is:

(i) the proportion of CO_2-neutral fuels blended into the fossil fuel, which can be up to 100%.

In Figure 6 we have summarised our own calculations of the LCA CO_2 emissions for a medium-sized passenger car with variations of selected driving factors. Here, we have based our calculations on the Frontier model for the calculation of life-cycle emissions for passenger cars, which we developed in 2019 as part of the study *Die CO2-Gesamtbilanz für Antriebstechnologien im Individualverkehr heute und in Zukunft – Lebenszyklusanalysen als Basis für zielführende Klimapolitik und Regularien*[24] (The overall CO2 impact for drive technologies in individual transport today and in the future – Life-cycle analyses as the basis for targeted climate policy and regulation). For the calculations, we have updated the following important assumptions in comparison to 2019:

(a) Assumptions on the carbon intensity of the electricity mix used to generate electricity for charging in the EU and in Germany: Both for Germany and the EU we have used the most up-to-date values that are available.[25]

(i) For the **EU average electricity mix** we assumed the same trend projections for the carbon intensity of electricity generation across the time period up to 2050[26] as we did in the 2019 study; however, the initial level was corrected down to the latest official figures.

---

24 See Frontier Economics (2019).

25 For the die EU see EEA (2023), for Germany see Federal Environment Agency (2023), as well as the long-term scenarios of the Federal Ministry for Economic Affairs and Climate Action (BMWK) (see Fraunhofer Institute for Systems and Innovation Research (ISI) (2022)) for the forecast (accessed in 12 July 2023).

26 Note: The example we have looked at is based on a vehicle that is manufactured in 2022 and has an assumed operating lifetime of 10 years. Accordingly, only relevant for the calculation in this case are the annual average electricity mixes up to and including 2032.

(ii) **For the electricity mix in Germany** we have looked at three different trend paths:

(A) Path (A) is based on the modelling in the long-term scenarios of BMWK (TN45 electricity), which, in line with the German Government's renewable energy expansion goals, assume that electricity in 2035 will 100% be produced from renewable energies.

(B) In path (B) we choose the same approach as the one described for the EU average under (i), i.e. the trend of the carbon intensity of electricity generation corresponds to the one set out in the study from 2019, albeit at a lower level.

(C) In path I we assume that the battery electric vehicle is 100% charged with renewable electricity. However, this applies solely to vehicles that are only charged e.g. with electricity from a photovoltaic system.

(c) Assumptions about the carbon intensity of the production of batteries, which we have also updated with the most recent values. Even if the electricity mix has less of an impact on CO_2 emissions in the production of batteries than it was assumed in our study in 2019, the CO_2 emissions from battery production vary depending on the production country and the battery type and/or chemical composition. For example, the composition of lithium-ion batteries – the most commonly used batteries today – can vary, among other things in terms of the nickel and cobalt proportion.

With regard to fuels, we take into account the current situation in which fuels with a higher proportion of blended CO_2-neutral fuels are increasingly available in petrol stations across Europe. For instance, since the start of 2023 diesel fuels with higher shares of CO_2-neutral fuels have been available at an increasing number of petrol stations in Germany (see Annex A.1); in France, for example, customers are filling up with a petrol fuel with an ethanol share of 85% (E85).[27] Against this background, in the calculations below we refer by way of example to diesel and petrol fuels with the following specifications:[28]

(a) Diesel fuel with a blending of 7% biofuel;

27 In France, the market share of the fuel Superéthanol (E85) in April 2022 even rose to 6.2% and thus doubled its share in comparison to 2020. See Euroactiv (2022).

28 Generally speaking, the assumptions underlying the calculations for the blending of CO_2-neutral fuels correspond to those that are applied in the LCA model of Frontier 2019. This approach is based on the assumption that e-fuels are blended into the fossil fuels as surrogates of the group of CO_2-neutral fuels or that e-fuels are used solely. The blending and/or use of HVO, bioethanol or other CO_2-neutral fuels are not analysed separately in this short study. This should be regarded as a conservative approach since the emissions identified for example according to the EU WTW JEC study (see Prussi et al. (2020)) for HVO are below the (indirect) CO_2 emissions modelled by us for the production of e-fuels.

(b) Diesel fuel with a share of 33% CO_2-neutral fuel blended in (in practice, this is currently predominantly HVO) – this corresponds e.g. to the brand “Klimadiesel25” (KD25, literally “climate diesel 25”), i.e. a reduction in CO_2 emissions by 25% (taking into account indirect emissions from fuel production) in comparison to a pure fossil fuel;[29]

(c) Diesel fuel consisting of 100% CO_2-neutral fuel[30] – this corresponds to the brand “Klimadiesel90” (KD90, literally “climate diesel 90”), i.e. a reduction in CO_2 emissions by 90% (taking into account indirect emissions from fuel production) in comparison to a pure fossil fuel (in practice, this is currently predominantly HVO);

(d) Petrol fuel with a blending of 5% biofuel (E5);

(e) Petrol fuel with a blending of 10% biofuel (E10);

(f) Petrol fuel with a blending of 85% CO_2-neutral fuel (this is currently predominantly ethanol fuel) – this corresponds to the designation E85 and is already on sale in countries like France.

(g) Petrol fuel consisting of 100% CO_2-neutral fuel – this is not yet available at petrol stations and therefore represents a hypothetical / future scenario. This fuel can be produced on a large scale and is technically suitable for use in petrol engines.

The example vehicle selected for the calculation of the LCA CO_2 emissions has the following characteristics:

(a) General characteristics
  (i) Vehicle type: Medium-sized car
  (ii) Year of purchase: 2022,
  (iii) Operating lifetime of vehicle: 10 years
  (iv) Annual mileage: 15,000 km
  (v) Region in which the vehicle is operated: Germany or EU

(b) Specific characteristics for the battery electric vehicle:
  (i) Electricity mix used for charging: Germany or EU average
  (ii) In the case of Germany, we designed three scenarios for how the carbon intensity of the electricity mix will have developed by 2032:
    (A) Significantly declining carbon intensity in line with the German Governm’nt's renewable energy expansion goals (share of electricity

29 In Sweden, the blending of 30% biodiesel is currently mandatory. See Euractiv (2023).

30 However, this fuel is not yet freely available to purchase, but it is already being issued to a closed group of users. The reason for this is that HVO 100 only reaches a density of 780 kg/m^3, whereas diesel products are required by law to achieve a minimum density of 800 kg/m^3. This “bureaucratic red tape” is the subject of criticism from proponents of HVO approval. See https://www.arcd.de/detail/biokraftstoffe-hilfestellung-fuer-verbrenner/

generated from renewable energies to reach 80% by 2030) and accelerated phase-out of fossil fuels;

(B) Moderately declining carbon intensity in line with the trend mapped out in our study from 2019.[31] This trend assumes that the medium-term goals of the German Government for the sector in relation to the year 2035 can practically only be implemented in part or not at all.

(C) Renewable electricity for charging: It is assumed that the vehicle is not charged using the German electricity mix, but instead charged exclusively with (remote) electricity from photovoltaic systems.

(iii) Carbon intensity of battery production: Range between 45 and 140 kgCO2e per kWh of storage capacity, which corresponds to the spectrum of the technical literature (see McKinsey & Company (2023), Popien et al. (2023b) and Lai et al. (2023)). Accordingly, a value of 45 kg/kWh corresponds roughly e.g. to battery production located in Sweden, a value of 75 kg/kWh to battery production in the USA.[32] The standard carbon intensities of lithium-ion batteries manufactured today for BEVs are on average (depending on type and production) between 90 kg/kWh and 110 kg/kWh[33] and up to 140 kg/kWh for average battery production in China[34].

(c) Specific characteristics for an internal combustion engine vehicle:

(i) Fuel: Diesel, petrol

(ii) Share of CO_2-neutral fuels – diesel: 7% (B7), 33% (KD25), 100% (KD90).

(iii) Share of CO_2-neutral fuels – petrol: 5% (E5), 10% (E10), 85% (E85)[35], 100% (not yet available on the open market, but general potential to be produced on a large scale and technically suitable for use in petrol engines).

---

31 See Frontier Economics (2019).

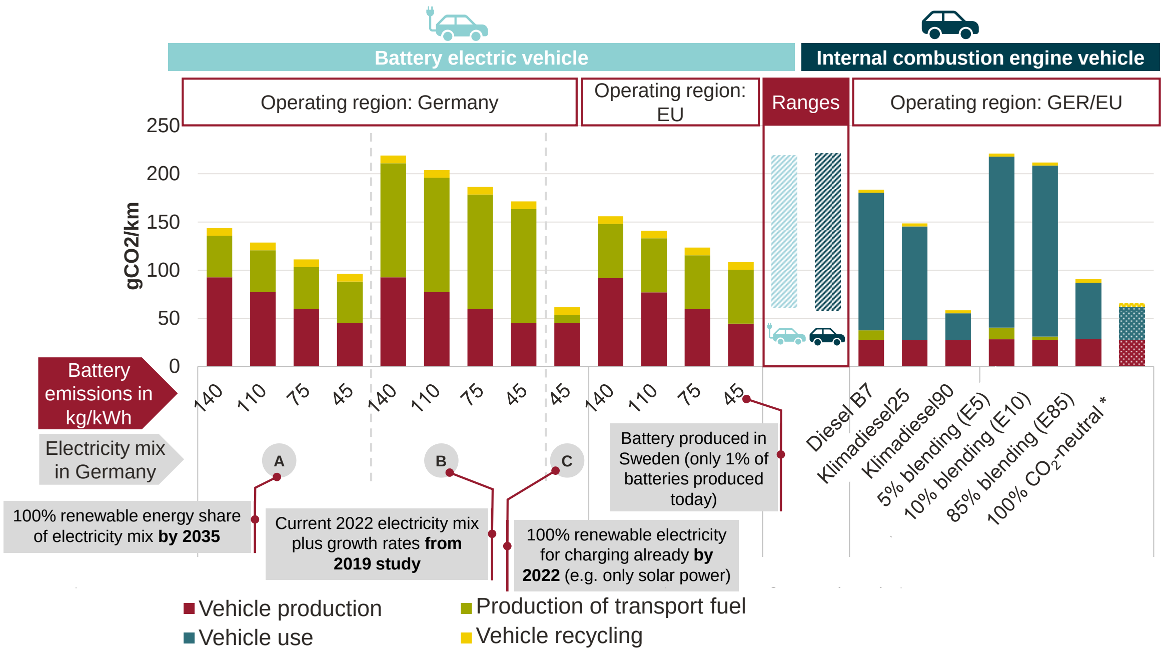
32 See McKinsey & Company (2023).

33 See Popien et al. (2023b).

34 See Lai et al. (2023).

35 The fuel E85 consists of 15% fossil petrol and 85% bioethanol. In comparison to a pure fossil fuel, depending on the plant-based raw material from which the bioethanol proportion is produced, a reduction in CO_2 emissions of around 63% can be achieved with E85 in relation to the life-cycle emissions of a vehicle. See Bunse et al. (2022). It must be taken into account here that the fuel E85 contains a 15% share of fossil fuel, i.e. bioethanol itself offers a CO_2 reduction of more than 70% in comparison to a pure fossil fuel. This represents approximately the same CO_2 reduction that can be achieved with e-fuels in our calculations.

Figure 6 CO_2 emissions of a medium-sized car in various scenarios on the basis of a life-cycle assessment (LCA)



Source: *Frontier Economics (2023)*

Note: **For petrol a proportion of 100% CO_2-neutral fuel is not yet normally available at petrol stations, which is why this bar is dotted.*

Under an LCA approach, the result is mixed in terms of the emissions impact of the drive technologies under the various scenarios.

(a) In cases with high blend-in rates of CO_2-neutral fuels – such as Klimadiesel90 – the internal combustion engine vehicle performs better than the battery electric vehicle in all scenarios in which a battery electric vehicle is charged using electricity with the average carbon intensity of power from the grid. Similar CO_2 emission values could only be attained by the battery electric vehicle if the vehicle was to be charged exclusively with renewable electricity. Plus, the battery would need to be manufactured in a country with a very low carbon intensity (e.g. Sweden).

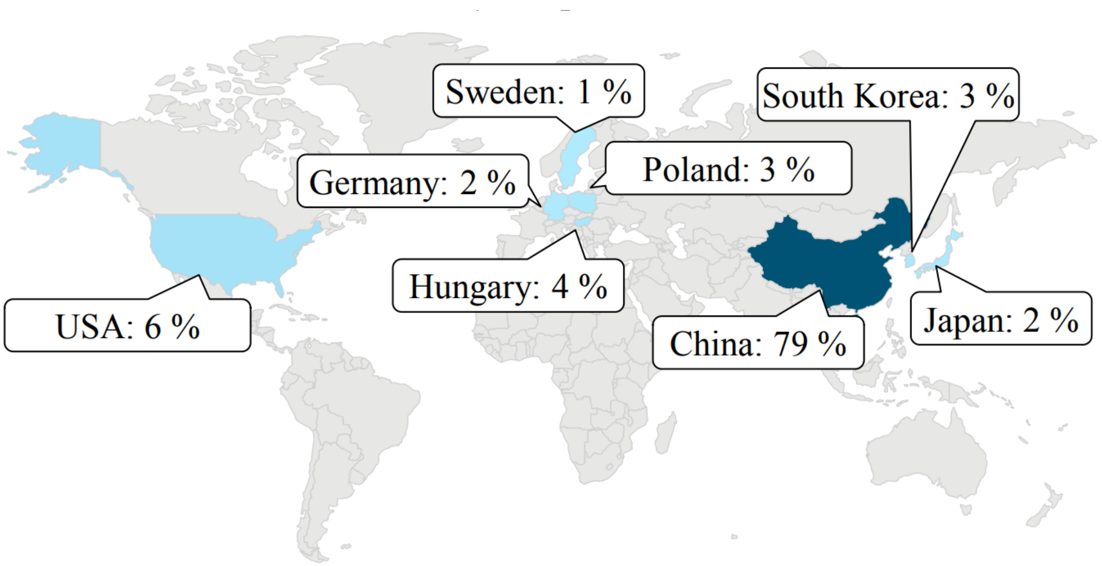
(b) The range of possible total LCA CO_2 emissions for the different scenarios overlaps in large parts. As a result, it is not possible to draw any sweeping conclusions about the advantageousness of the different drive systems (i.e. battery electric or internal combustion engine).

(c) Even within battery electric vehicles, the range of LCA CO_2 emission outcomes is still wide. These variations arise particularly at the stages of manufacturing and energy supply (WTT) and would not be picked up by a TTW approach.

Objections could be raised against the above considerations that climate-friendly fuel types like KD90 and KD25 are only being used in very limited amounts at present. However, this is irrelevant for the issue of whether the LCA approach or the TTW approach is more appropriate within the regulatory framework of determining CO2 emissions. Significant from a climate policy perspective is that these technologies are generally available and can therefore potentially be established in the market if they prove to be cost effective.

In addition, it needs to be considered that likewise for battery electric vehicles declining CO_2 emission outcomes can only be achieved through declining carbon intensities of the electricity mix and, in particular, through lower carbon intensities in battery production. However, at present a majority of battery cells manufactured worldwide is (still) produced in the China (Figure 7). Here again, as is the case with CO_2-neutral fuels, the effort to reduce and eliminate CO_2 emissions is a dynamic process, and one that – for a large part – will still need to be delivered in the future. Focusing solely on the TTW stage offers no incentives to intensify emission reduction efforts, like for example by rewarding battery manufacturers who employ manufacturing techniques with a low carbon intensity.

Figure 7 Average production share of battery cells in 2021



Sou rce: Popien et al. (2023a)

4.2 Even from EU Commission calculations it can be concluded that internal combustion engine vehicles powered by CO_2-neutral fuels can achieve a better carbon footprint than electric vehicles

As part of the impact assessment for the revision of the fleet emission targets[36], the EU Commission has discussed and evaluated the results of its commissioned study conducted by Ricardo Energy & Environment[37] on the climate footprint of various drive types.

It should be noted that, CO_2-neutral fuels were not explicitly included in the analyses of technologies because – according to the authors of the study – the data situation was insufficient and therefore the uncertainty associated with the results was very high. However, if the results are interpreted correctly and 100% CO_2-neutral fuels are taken into account (as in Figure 8), then the results show that internal combustion engines powered by CO_2-neutral fuels would cause lower emissions than battery electric vehicles (BEV), even in cases in which the electricity mix is based on 100% renewable energy sources (which is not to be expected to be realized across Europe before 2040). In addition – in contrast to considerations in the fleet emission target regulations – the study indicates that battery electric vehicles generate higher CO_2 emissions in the vehicle manufacturing phase.

These statements can be derived as follows:

(a) In the case of internal combustion engine vehicles, the results of the Commission (Figure 8) make the assumption that predominantly fossil fuels are used. If instead CO_2-neutral fuels are considered, the combined fuel-related emission balance for production (WTT) and use (TTW) results in much lower outcomes compared to the original "well-to-wheel" (WTW) emissions set.

(b) WTW combines the emissions for the two stages WTT and TTW.[38] The resulting net CO_2 emissions in the second step are therefore significantly lower than the original emissions for pure fossil fuels.[39] (No. 2 in Figure 8).

(c) In contrast to battery electric vehicles (BEV) charged with an average electricity mix for the EU-28 (green line), a clear reduction in emissions can be seen in the third step.

---

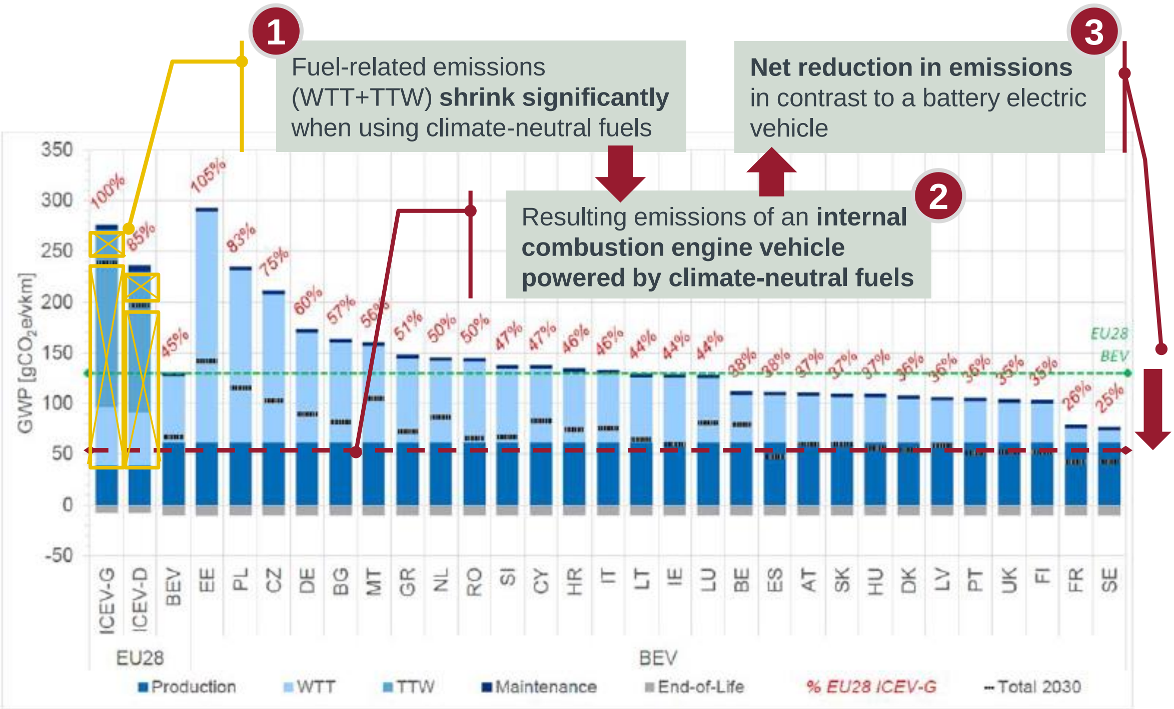
36 See European Commission (2021b).

37 See European Commission (2020a)

38 The reason for this is the virtually CO_2-neutral production of synthetic fuels. The greenhouse gases emitted in the TTW stage were previously removed from the atmosphere in the WTT stage. The negative emissions generated this way at the WTT stage offset the TTW emissions accordingly. Nonetheless, from a LCA perspective the carbon footprint is not exactly zero unless the construction and operation of the renewable energy plants and the conversion facilities are completely climate neutral too. The corresponding CO_2 burden of the facilities needs to be taken into account accordingly.

39 The line drawn in the diagram serves only to illustrate the approximate resulting order of magnitude and is not based on our own modelling (in contrast to the previous section).

Figure 8 LCA emissions of a vehicle in the lower mid-size class (CO_2-neutral fuels added)



Source: *European Commission (2020a), Figure ES5, plus European Commission (2021b), Figure 39 (added by Frontier Economics).*

Note: *BEV = battery electric vehicle, ICEV = internal combustion engine vehicle, WTT = well-to-tank (emissions from fuel/electricity production), TTW = tank-to-wheel (emissions from the use phase: tailpipe emissions, zero emissions in vehicles with a purely electric drive)*

The evaluation of the EU Commission's calculations with regard to the use of CO_2-neutral fuels confirms the result of our own calculations in section 4.1, i.e. that internal combustion engine vehicles powered by CO_2-neutral fuels can have lower total life-cycle CO_2 emissions than battery electric vehicles of the same type. Therefore it is evident that sweeping conclusions about the advantageousness of particular drive technologies are not appropriate, and that instead the outcome depends much more on the specifics of the individual case in question (for example, whether the fuels are CO_2-neutral fuels or fossil fuels).

These simple illustrations show that regulatory instructions like Regulation (EU) 2023/851 should be based on an LCA approach that assesses the real, climate-effective emission balance of different drive solutions. By contrast, by labelling certain types of vehicles as "emission-free", the TTW approach masks their actual carbon footprint. Regulation 2023/851 is based solely on the TTW approach, which means that the considerations underlying the LCA approach are not reflected in the content of the regulations.

5 The LCA approach is becoming increasingly established in technical literature and regulations

5.1 The adoption of life-cycle assessments is now the standard approach in technical literature

In technical literature relating to the analysis and calculation of CO_2 emissions in the road transport sector, the use of life-cycle methods has now become established as the standard. As part of a meta-analysis, in 2020 we identified 85 international studies from the previous 15 years that performed life-cycle assessments of CO_2 emissions of various drive technologies in passenger cars.[40] Generally individual study results are scenario-dependent, but in terms of basic conclusions these studies leave no doubt as to the need to apply the LCA approach to calculations of carbon footprints.

Due to the progressive development of innovative drive technologies, the technical literature on CO_2 emissions in road transport is growing steadily. The most recent studies also predominantly use life-cycle methods.[41]

5.2 LCA approaches are now also established in regulation policy

In an increasing number of regulatory areas, the adoption of life-cycle assessments for the calculation of the carbon intensity of different technologies and applications has taken place or is at least referenced to.

Even in 2020 the so-called Taxonomy Regulation (Regulation (EU) 2020/852)[42] set out that, when examining the environmental impact of commercial activities in terms of environmental objectives, beyond the activities themselves the life cycle of the goods and services provided should also be taken into account.[43]

In April 2023 it was then formulated in the Amendment Regulation (EU) 2023/851 that a joint European Union method for assessing and reporting CO_2 emissions across the entire life cycle of passenger cars and light commercial vehicles should be developed.[44]

---

40 See Frontier Economics (2020), *Cradle-to-Grave-Lebenszyklusanalyse im Mobilitätssektor - Metastudie zur CO2-Bilanz alternativer Fahrzeugantriebe* (Cradle-to-grave life-cycle assessments in the mobility sector – Meta-study on the carbon footprint of alternative vehicle drive systems).

41 See e.g. Degen and Schütte (2022), Popien et al. (2023a), Lai et al. (2023) and McKinsey & Company (2023).

42 Regulation (EU) 2020/852, eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32020R0852

43 Regulation (EU) 2020/852, eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32020R0852, point 34

44 Regulation (EU) 2023/851, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32023R0851, points 33-34

In February 2023 the EU Commission also adopted two Delegated Acts in its Renewable Energy Directive. The first Delegated Act includes a definition of the criteria for the production of renewable liquid or gaseous fuels of non-biological origin (RFNBO) in order to ensure that these fuels can only be produced from "additional" renewable electricity and hydrogen generated at the same time and in the same area.[45] The second Delegated Act sets out that the emissions throughout the entire life cycle of the fuel must be taken into account in the calculation of the greenhouse gas savings of RFNBO.[46] These include, among other things:

(a) upstream emissions associated with the production of the fuel,

(b) emissions due to the grid power supply, as well as

(c) emissions associated with the processing, transport and use of the fuel at the end consumer,

(d) minus the emission savings due to the separation and geological storage of CO_2.

Overall, these requirements reflect an LCA approach to the calculation of CO_2 emissions of RFNBO within the framework of the regulation, whereas in the fleet emission targets neither green electricity criteria nor a methodology for assessment of full life-cycle emissions are applied.

At the same time, the EU Commission itself had considered the adoption of life-cycle analyses for the evaluation of the greenhouse gas emissions of conventional vehicles and vehicles powered with alternative drive systems. In the 2019 regulations that define CO_2 emission performance standards for passenger cars and light commercial vehicles[47] as well as for heavy goods vehicles[48], there are provisions that the emissions of such vehicles that are brought onto the roads of the European Union must be assessed across the entire life cycle. In order to do this, by 2023 the Commission was to explore the possibility of developing an appropriate methodology and presenting suitable follow-up measures and, if applicable, legislative proposals.[49] However, this undertaking was pushed back to December 2025 with the amended Regulation (EU) 2023/851 of 19 April 2023 amending Regulation (EU) 2019/631 with regard to strengthening the CO2 emission performance

45 Delegated act for Regulation (EU) 2018/2001, https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf

46 Annex of the delegated act for Regulation (EU) 2018/2001, https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_annexe_acte_autonome_part1_v4.pdf

47 Regulation (EU) 2019/631, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631

48 Regulation (EU) 2019/1242, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1242&qid=1689162171924

49 Regulation (EU) 2019/631 and 2019/1242, Article 15(2).

standards for new passenger cars and new light commercial vehicles[50]; see explanations in section [2].

In 2017, DG Klima was commissioned to carry out a study in which a life cycle-based approach was to be developed for the road transport sector and to be applied to sample vehicle categories, drive technologies and fuels.[51] However, in 2021 the Commission ultimately arrived at the conclusion that the suitability of the methodology that was developed as part of the study was limited in terms of calculating individual life-cycle emissions for individual vehicles.[52] In particular, only the need to develop an even more detailed and more complex approach was emphasised.[53] However, together with the large number of LCA analyses being carried out for vehicle emissions, the fact that the LCA approach is being applied in different areas of European regulations and in relation to the global greenhouse gas accounting standards indicates that an LCA approach can generally be implemented in the regulation of the fleet emission targets in practice.

In addition, the study commissioned by the EU Commission confirms that, ultimately, only through a life-cycle approach is it possible to make a meaningful comparison between different vehicle technologies and fuels.[54] Although the study concludes that battery electric vehicles offer the lowest life-cycle emissions for the investigated drive technologies both now and in the future[55], the authors also pointed out the limitations of the analyses that were performed. For example, according to the authors of the study e-fuels were not explicitly included in the technology analysis because the data situation was insufficient and therefore the uncertainty associated with the results was very high.[56] For this reason, the authors also explicitly pointed out that the study results did not allow for definitive assessment of the relative environmental impacts of the different fuel chains to be performed.[57] They therefore recommend that not only the data basis for innovative fuel production techniques such as e-fuels should be improved, but also the calculation methods, to enable better comparison of the different fuel chains.[58]

---

50 Regulation (EU) 2023/851, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32023R0851

51 Ricardo Energy & Environment was commissioned to carry out the study. The final report *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA* was completed in July 2020 and published. See European Commission (2020).

52 See European Commission (2021b), page 100.

53 See European Commission (2021b), page 100.

54 See European Commission (2020a), page 6.

55 Ibid., page 11.

56 Ibid., page 190.

57 Ibid., page 196.

58 Ibid., page 206.

LCA methods are also being adopted ever increasingly at a global level and beyond the transport sector. In the European regulatory framework, LCA have already been playing a role since the 1990s.[59] The concept of assessing environmental impacts across the entire life cycle of products "from the cradle to the grave" was anchored for the first time in Council Regulation (EEC) No 880/92 on a eco-label award scheme for clean products.[60] Directive 2005/32/EC on establishing a framework for the setting of ecodesign requirements for energy-using products also defines the environmental impacts of a product across its entire life cycle.[61] The LCA concept can also be found in further regulations and directives relating e.g. to waste materials[62], energy labelling[63] and biofuels[64], as well as in various other projects such as the Circular Economy Action Plan[65] and the'EU's biodiversity strategy[66].

At a global level, the initiative *Greenhouse Gas Protocol* is working with governments, associations, companies and NGOs to develop globally standardised accounting and reporting methods for greenhouse gas emissions. The standard developed for this purpose divides the greenhouse gas emissions of an organisation into three different areas (Scope 1, 2 and 3 emissions).[67] Scope 1 and Scope 2 emissions cover direct emissions that stem from sources that are owned or controlled by the company (Scope 1) as well as indirect emissions associated with the purchase of electricity and other forms of energy (Scope 2).[68] By contrast, Scope 3 emissions include all other indirect emissions that occur over the entire value chain of the reporting company, including upstream and downstream emissions.[69] The calculation approach for determining Scope 3 emissions thus follows a life-cycle based approach. These standards are already being applied in practice. For example, companies who have adopted self-imposed (voluntary) emissions reduction targets as part of the Science Based Targets Initiative (SBTi) are also required to include their Scope 3 emissions in their target attainment calculations.[70]

---

59 See Sala et. al (2021).

60 Council Regulation (EEC) No 880 /92, articles 3 and 5(4), https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:31992R0880.

61 Directive 2005/32/EC, section 2, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:191:0029:0058:DE:PDF.

62 Directive 2008/98/EC, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32008L0098.

63 Directive 2010/30/EU, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0001:0012:DE:PDF.

64 Directive (EU) 2015/1513, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32015L1513.

65 See European Commission (2020b).

66 See European Commission (2020c).

67 See Greenhouse Gas Protocol Guidance https://ghgprotocol.org/guidance-0, accessed on 12 July 2023.

68 Only the emissions generated directly at the point of energy generation are recorded in the category of Scope 2 emissions. See Greenhouse Gas Protocol (2023a), page 27.

69 See Greenhouse Gas Protocol (2023b), page 5.

70 See SBTi (2023), page 17.

6 The distortion of the technology selection process has negative consequences and runs counter to the objectives of climate protection

The use of a TTW approach when applied to the regulation of individual sectors involves the risk of distortion and disincentives (section 6.1). This can potentially run counter to the objectives of climate protection (section 6.2).

6.1 If the TTW approach is applied then there is a risk that reducing CO_2 emissions is not appropriately incentivised

To ensure that the comparison of technologies is comprehensive, all emissions caused by a vehicle in other sectors or in other countries should be attributed accordingly to the vehicle; e.g. in the energy sector during the production of the transport fuel or in the industry sector, possibly in a country outside of Europe, during the manufacture of the vehicle or vehicle components, as is the case in particular with the batteries (more on this in the next section). An approach that includes only the European transport sector is less relevant in terms of achieving the overall climate goals – particularly in connection with the discussion about sector coupling.

An approach like tank-to-wheel, which has an isolated focus on a single stage in the life cycle, can distort effective climate protection as it incentivises the use of technologies that specifically reduce emissions in that single phase (in this case tank-to-wheel) without taking into account the emissions in the other phases. This can lead to a number of downsides:

- **Inefficiency**: Separate CO_2 reduction efforts within individual life-cycle stages lead to inefficiencies in comparison to a comprehensive CO_2 reduction strategy since synergies across stages are much more difficult to identify and exploit.
- **Ineffectiveness**: In some cases, emissions are not avoided – instead, they are simply moved from one life-cycle stage to another, which can even lead to an increase overall. When using a TTW approach, the players involved may choose technologies that do indeed reduce the CO_2 emissions at the TTW stage but do not lead to a reduction in terms of the overall climate impact. In this case, no contribution is made to climate protection. To what extent this can occur depends on a large number of factors, but particularly on the interaction between the incentives and support schemes for the relevant technologies in order to lower CO_2 emissions across all value chain and life-cycle stages.

6.2 If the LCA approach is adopted then emissions may potentially be shifted to other countries

In terms of the greenhouse effect, it does not matter where emissions are generated and released geographically in the world. For this reason it is important to not only account for greenhouse gas emissions that stem from the production of vehicles in Germany or in the EU, but also for those that are generated in supplier countries such as China. Ultimately for the climate, it is irrelevant whether the CO_2 emissions are low or zero during the vehicle use phase (TTW) but high at other stages of the lifecycle.

CO_2 emissions generated outside of the EU (in particular in battery cells manufacturing) are systematically not taken into account and assessed by a TTW approach. Shifting CO_2 emissions to countries outside of Europe may be beneficial for certain players within the EU in meeting their climate targets, but there is no benefit for global climate protection.

The EU has recognised that the regulatory mechanisms in the European Union risk shifting CO_2 emissions to other countries (a process referred to as "carbon leakage") and that rising CO_2 emissions in other parts of the world caused by imports can undermine the efforts made by the EU to reduce its global carbon footprint, even if the EU manages to significantly improve its internal greenhouse gas emission balance.[71]

The Carbon Border Adjustment Mechanism (CBAM) created (to date only) for certain goods is a climate protection measure that is designed to assist the reduction of global greenhouse gas emissions and prevent the risk of carbon leakage.[72] However, CBAM started in October 2023 with a transitional phase in which importers of goods are only required to report the embedded emissions of their products, but without incurring any financial liabilities.[73] This transitional phase is due to run until the end of 2025, and only after this point will carbon levies come into force. In addition, the mechanism will initially only be applied to the following goods with high potential for carbon leakage: aluminium, iron, steel, fertilizers, electricity, hydrogen and cement. The mechanism hereby takes into account both direct and indirect emissions from the manufacturing of these products.

---

71 Regulation (EU) 2023/956 establishing a Carbon Border Adjustment Mechanism, recitals 8 and 9.

72 Regulation (EU) 2023/956 establishing a Carbon Border Adjustment Mechanism, recital 15, see also recital 81 and Article 1(1).

73 See European Commission (2023).

7 Conclusions

Overall, the use of an LCA approach for determining CO_2 emissions of products and technologies is consistent with the current scientific state-of-the-art and should be deemed appropriate, in contrast to a TTW approach.

A national or even EU-wide sector-specific approach such as the fleet emission targets provides only little insight into the actual climate impact of a particular technology. This requires a systematic analysis based on a cross-sector, global and time-unrestricted system boundary. This systematic approach of life-cycle assessments account for CO_2 emissions across the entire life cycle of the drive technology and thus illustrates the climate impact comprehensively.

8 Bibliography

- BMUV (2023), FAQ – Fleet CO_2 threshold values, date: 8 March 2023, https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Verkehr/co2_flottengrenzwerte_faq_230308_bf.pdf

- Bunse et al. (2022), Greenhouse gas abatement costs for passenger cars, Bunse, Mark et al., studio Gear Up B.V., study on behalf of ePURE, May 2022, https://www.studiogearup.com/wp-content/uploads/2022/05/2022_sGU-for-ePURE_Greenhouse-gas-abatement-costs-for-passenger-cars-DEF.pdf

- Dai et al. (2019), Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications, Dai, Qiang et al., Batteries No. 5, Vol. 48, 2019, https://www.mdpi.com/2313-0105/5/2/48

- Degen and Schütte (2022), Life-cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production, Degen, Florian und Schütte, Marius, Journal of Cleaner Production, Vol. 330, 1 January 2022.

- EEA (2023), Greenhouse gas emission intensity of electricity generation, European Environment Agency (EEA), accessed on 12 July 2023, https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-13#tab-googlechartid_chart_11

- Euractiv (2022), Sales of high-blend ethanol surge in France amid rising fuel prices, Goulding Carroll, Sean, 20 June 2022, https://www.euractiv.com/section/biofuels/news/sales-of-high-blend-ethanol-surge-in-france-amid-rising-fuel-prices/, accessed on 12 July 2023.

- Euractiv (2023), Swedish climate minister dismisses far-right's biofuel threats, Szumski, Charles, 12 April 2023, https://www.euractiv.com/section/politics/news/swedish-climate-minister-dismisses-far-rights-biofuel-threats/, accessed on 13 July 2023.

- European Commission (2020a), Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Final Report for the European Commission, DG Climate Action, Ricardo Energy & Environment, 13 July 2020, https://climate.ec.europa.eu/system/files/2020-09/2020_study_main_report_en.pdf

- European Commission (2020b), COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS – A new action plan for the circular economy – For a clean and more competitive Europe, Brussels, 11 March 2020, https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0016.02/DOC_1&format=PDF

- European Commission (2020c), COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS – EU biodiversity strategy for 2030 – More space for nature in our lives, Brussels, 20 May 2020, https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0002.02/DOC_1&format=PDF

- European Commission (2021a), European Green Deal: The Commission proposes a realignment of economy and society in the EU in order to meet the climate targets, press release, Brussels, 14 July 2021, https://ec.europa.eu/commission/presscorner/detail/de/IP_21_3541

- European Commission (2021b), COMMISSION STAFF WORKING DOCUMENT – IMPACT ASSESSMENT, Part 2, Accompanying the document – Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition, Brussels, 14. July 2021, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0613.

- European Commission (2023), adjustment of the CO_2 threshold value (CBAM): The EU Commission consults on reporting obligations, press release, representation in Germany, 13 June 2023, https://germany.representation.ec.europa.eu/news/anpassung-des-co2-grenzwertes-cbam-eu-kommission-konsultiert-zu-den-berichtspflichten-2023-06-13_de

- Fraunhofer ISI (2022), Long-term scenarios for transformation of the energy system in Germany, greenhouse gas-neutral scenarios T45, Dr. Frank Sensfuß, 15 November 2022, https://www.langfristszenarien.de/enertile-explorer-wAssets/docs/LFS3_T45_Szenarien_15_11_2022_final.pdf and Scenario Explorer https://langfristszenarien.de/enertile-explorer-de/szenario-explorer/, accessed on 12 July 2023.

- Frontier Economics (2019), *Die CO2-Gesamtbilanz für Antriebstechnologien im Individualverkehr heute und in Zukunft – Lebenszyklusanalysen als Basis für zielführende Klimapolitik und Regularien* (The total carbon footprint of drive technologies in private transport today and in the future – Life-cycle analyses as the basis for target-oriented climate policy and regulations), study performed on behalf of UNITI Bundesverband mittelständischer Mineralölunternehmen e. V., November 2019, https://www.efuel-alliance.eu/fileadmin/Downloads/RPT-Frontier-Uniti-LCA-26-11-2019.pdf

- Frontier Economics (2020), *Cradle-to-Grave-Lebenszyklusanalyse im Mobilitätssekt–r - Metastudie zur CO2-Bilanz alternativer Fahrzeugantriebe* (Cradle-to-grave life-cycle assessments in the mobility sector – Meta-study on the carbon footprint of alternative vehicle drive systems), Frontier Economics on behalf of Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV, German research association for internal combustion engines), June 2020

- Greenhouse Gas Protocol (2023a), GHG Protocol Scope 2 Guidance – An amendment to the GHG Protocol Corporate Standard, World Resources Institute, Sotos, Mary, https://ghgprotocol.org/sites/default/files/2023-03/Scope%202%20Guidance.pdf

- Greenhouse Gas Protocol (2023b), Corporate Value Chain (Scope 3) Accounting and Reporting Standard – Supplement to the GHG Protocol Corporate Accounting and Reporting Standard, World Resources Institute, Bhatia, Pankaj et al., https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

- Joanneum Research Life (2019), *Treibhausgasemissionen und Primärenergieverbrauch in der Lebenszyklusanalyse von PKW-basierten Verkehrssystemen* (Greenhouse gas emissions and primary energy consumption in the life-cycle assessment of passenger car-based transport systems), Jungmeier, Gerfried et al., study on behalf of Österreichischer Automobil- und Touringclub (ÖAMTC, Austrian Motor Club), FIA and ADAC, September 2019.

- Lai et al. (2023), Investigating greenhouse gas emissions and environmental impacts from the production of lithium-ion batteries in China, Lai, Xin et al., Journal of Cleaner Production, Vol. 372, 20 October 2022.

- McKinsey & Company (2023), The race to decarbonize electric-vehicle batteries, Linder, Martin et al., 23 February 2023, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-race-to-decarbonize-electric-vehicle-batteries#/.

- Popien et al. (2023a), Comparison of lithium-ion battery supply chains – a life cycle sustainability assessment, 30th CIRP Life Cycle Engineering Conference, Popien, Jan-Linus et al., Procedia CIRP 116 (2023), pages 131–136.

- Popien et al. (2023b), Comparative sustainability assessment of lithium-ion, lithium-sulphur, and all-solid-state traction batteries, Popien, Jan-Linus et al., The International Journal of Life Cycle Assessment (2023) 28, pages 462-477.

- Prussi et al. (2020), JEC Well-To-Wheels report –5 - Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, Prussi, M., JRC (the Joint Research Centre of the European Commission), EUCAR and Concawe, Publication Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC121213#:~:text=As%20an%20update%20of%20the,Europe%20in%202025%20and%20beyond

- Ricardo (2023), Research for TRAN Committee – Environmental challenges through the life cycle of battery electric vehicles, Hill, Nikolas, Raugei, Marco et al., study for the Committee on Transport and Tourism of the European Parliament, March 2023, https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733112/IPOL_STU(2023)733112_EN.pdf

- Romare und Dahllöf (2017), The Life-Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries – A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles, IVL Swedish Environmental Research Institute, study on behalf of the Swedish Energy Agency (Energimyndigheten) and the Swedish Transport Administration (Trafikverket), May 2017

- Sala et. al (2021), The evolution of life cycle assessment in European policies over three decades, The International Journal of Life Cycle Assessment (2021), Vol. 26, pages 2295–2314, https://doi.org/10.1007/s11367-021-01893-2.

- SBTi (2023), SBTi CORPORATE MANUAL, TVT-INF-002, Version 2.1, April 2023, https://sciencebasedtargets.org/resources/files/SBTi-Corporate-Manual.pdf

- Federal Environment Agency (2023), *CO_2-Emissionen pro Kilowattstunde Strom stiegen in 2022* (CO_2 emissions per kWh of electricity rose in 2022), accessed on 12 July 2023, https://www.umweltbundesamt.de/themen/co2-emissionen-pro-kilowattstunde-strom-stiegen-in#:~:text=Die%20Erzeugung%20einer%20Kilowattstunde%20Strom,bei%20369%20Gramm%20pro%20Kilowattstunde.

- VDI (2020), *Ökobilanz von PKWs mit verschiedenen Antriebssystemen* (Environmental performance evaluation of passenger cars with different drive systems), Koch, Thomas et al., Karlsruher Institut für Technologie on behalf of VDI Verein Deutscher Ingenieure e.V., October 2020, https://www.vdi.de/fileadmin/pages/vdi_de/redakteure/vor_ort/bv/braunschweiger-bv/news/News_BV/VDI-Studie_Oekobilanz-PKW_Internet.pdf

Annex A – Annex

A.1 Overview of petrol stations offering Klimadiesel25 and Klimadiesel90

Table 2 Overview of petrol stations offering Klimadiesel25 and Klimadiesel90

KD25	KD90	Petrol station	Address	Availability
	✓	Tramin Tankcenter Hafen	Rhein- Ecke Elbestrasse, 45478 Mülheim	End of 2023
	✓	RHV petrol station Bad Hersfeld	Konrad-Zuse-Strasse 8, 36251 Bad Hersfeld	Summer 2023
	✓	RHV petrol station Frankfurt-Kalbach	Josef Eicher Str. 8, 60437 Frankfurt	Summer 2023
	✓	Tramin Tankcenter Osterfeld	Bottroper Strasse 228, 46117 Oberhausen	From July 2023
	✓	Tramin Tankcenter Saarn	Kölner Strasse 89, 45481 Mülheim	From July 2023
✓		team energie petrol station	Berliner Chaussee 96, 39114 Magdeburg	From 07 July 2023
✓		team energie petrol station	Marie-Curie-Strasse 1, 24837 Schleswig	From July 2023
	✓	RHV petrol station Eichenzell-Welkers	Am Langen Acker 17, 36124 Eichenzell	From June 2023

KD25	KD90	Petrol station	Address	Availability
	✓	RHV petrol station Baunatal	Salzgitter-strasse 28, 34225 Baunatal	From June 2023
✓		TAS petrol station Höxter	Brenkhäuser Str. 44, 37671 Höxter	From 01 June 2023
✓		TAS petrol station Wesertal	Mühlenplatz 4, 34399 Wesertal	From 01 June 2023
✓		TAS petrol station SZ-Salder	Museumstrasse 50, 38229 Salzgitter-Salder	From 01 June 2023
✓		team energie petrol station	Altländer Strasse 29, 21680 Stade	From 01 June 2023
✓		team energie petrol station	Eckernförder Strasse 207, 24119 Kiel-Kronshagen	From 31 May 2023
✓		team energie petrol station	Marie-Curie-Ring 45, 24941 Flensburg	From 24 May 2023
	✓	BFT Willer	Gutenbergstrasse 80-86, 24118 Kiel	From 10 May 2023
✓		CLASSIC petrol station	Giflitzer Strasse 12, 34537 Bad Wildungen	From 10 May 2023
✓		Joiss petrol station	Salzuflener Strasse 68, 32602 Vlotho-Valdorf	From 26 April 2023
✓		Joiss petrol station	Berenbosteler Strasse 92, 30823 Garbsen	From 26 April 2023
✓		FELTA petrol station	Celler Str. 25, 29525 Uelzen	From 26 April 2023
✓		CLASSIC petrol station	Auricher Strasse 68, 26556 Westerholt	From 19 April 2023

KD25	KD90	Petrol station	Address	Availability
✓		CLASSIC petrol station	Kirchweyher Strasse 4, 28844 Kirchweyhe	From 18 April 2023
✓		CLASSIC petrol station	Angelser Str. 2, 28844 Weyhe (Leeste)	From 18 April 2023
	✓	Tramin Tankcenter Heisingen	Heisinger Strasse 487, 45269 Essen	From 01 April 2023
✓		FELTA petrol station	Mühlenstrasse 30, 49401 Damme	From April 2023
✓		CLASSIC petrol station	Oststrasse 28, 33129 Delbrück	From 30 March 2023
✓		WEVAG petrol station	Dingdener Strasse 183 – 187, 46395 Bocholt	From 30 March 2023
✓		Brämswig petrol station	Daimlerstrasse 2, 49393 Lohne (Oldenburg)	From 24 March 2023
✓		CLASSIC petrol station	Uerdinger Strasse 108a, 47441 Moers	From 27 March 2023
✓		Joiss petrol station	Burgstrasse 36, 27243 Harpstedt	From 03 March 2023
✓		Joiss petrol station	Nienburger Strasse 10, 27232 Sulingen	From 03 March 2023
✓		FELTA petrol station	Rathausstrasse 5, 26826 Weener	From 16 February 2023
✓		FELTA petrol station	Steinhauser Strasse 14, 26345 Bockhorn	From 13 February 2023
✓		FELTA petrol station	Münsterstrasse 45, 49186 Bad Iburg	From 10 February 2023
✓		FELTA petrol station	Falkenrotter Str. 163, 49377 Vechta	From 08 February 2023
✓		FELTA petrol station	Visbeker Damm 1, 49429 Visbek	From 07 February 2023

KD25	KD90	Petrol station	Address	Availability
✓	✓	CLASSIC petrol station	Auf dem Kuhkamp 21, 27318 Hoya	From 03 February 2023

Source: *https://klima-kraftstoffe.de/tankstellen*
Note: *KD90 was not yet freely available to purchase when this study was compiled.*

A.2 Assumptions for the selective model adjustments

The model for the calculation of life-cycle emissions has been selectively updated. Changes were made to the assumptions for the electricity mix of the EU and Germany, as well as to the underlying CO_2 emissions in battery production.

Assumptions for the carbon intensities of electricity generation:

(a) Carbon intensity in the EU electricity mix – most recent data for the carbon intensity of the European electricity mix is from 2021 and set out 238 gCO_2/kWh on average (see EEA (2023)). The 2019 study projected 281 gCO_2/kWh for 2021, which was calculated from the forecasts of the IEA World Energy Outlook (2018) for electricity generation. We retain the declining carbon intensity trend in the update. As a result, e.g. carbon intensity will drop to 141 gCO_2/kWh on average in the European electricity mix by 2030 (in comparison to 172 gCO_2/kWh according to our 2019 study). According to the EEA (2023), in order to achieve the 55% reduction in greenhouse gas emissions targeted by the EU's Fit-for-55 initiative, the carbon intensity in the European electricity mix needs to be at least as low as 118 gCO_2/kWh by 2030.

(b) Carbon intensity in the electricity mix in Germany

   (i) Electricity mix (A) – Here, we apply the most recent figure from 2022 for the carbon intensity of the electricity mix, which is 434 gCO_2/kWh (see Federal Environment Agency (2023)). We take into account the German Government’s emission reduction targets for the electricity sector up to the year 2035 and assume that nearly 100% of the electricity in 2035 will be produced from renewable energies. Consequently, the carbon intensity of the electricity mix would only be 64 gCO_2/kWh by 2030 and 27 gCO_2/kWh by 2035. Even if all electricity is generated from renewable energies, the carbon intensity will still not be zero as the construction and operation of the renewable energy facilities includes a CO_2 burden that would continue to be attributed to this electricity.

   (ii) Electricity mix (B) – (Approach analogous to (a)) – The most recent number for the carbon intensity of the electricity mix in Germany is 434 gCO_2/kWh in 2022 (see Federal Environment Agency (2023)). The 2019 study expected a value of 443 gCO_2/kWh for 2022, which was calculated from the forecasts of the BMWI for electricity generation. Here again we have adopted the declining rates from the 2019 study. As a result, e.g. only 341 gCO_2/kWh is projected for the European electricity mix by 2030 (in contrast to 348 gCO2/kWh in our 2019 study). However, 2022 saw higher than expected carbon intensities on account of the gas crisis in Europe. By 2021 the carbon intensity only dropped to 420 gCO_2/kWh.

(iii) Electricity mix (C) – We make the assumption that the vehicle will be charged using electricity from 100% renewable energy sources, i.e. we assume that the electricity will have a carbon intensity of only 27 gCO_2/kWh, even in 2022. In 2022, this scenario is only realistic for a vehicle that is charged remotely with privately generated solar electricity, thus without a connection to the grid (e.g. from a photovoltaic system installed on the roof of the user's own house or place of work).

Emissions from battery production were calculated in the 2019 study using carbon intensities of electricity generation in the battery manufacturing countries combined with data on battery production from Romare and Dahllöf (2017). The general availability of data relating to battery production and associated CO2 emissions was limited at the time of publishing the Frontier Economics (2019) study. The data situation has improved significantly since then, which is why we have now based the calculations of CO_2 emissions on more up-to-date data. It has generally been observed by other studies that, in addition to the country of manufacturing (see e.g. Figure 9), the type and the composition of the chemical components of the battery (see e.g. Figure 10) play a significant role in particular. In order to reflect these aspects in our analysis, for our calculations we take into account a range of different battery production emission values. We use the following values:

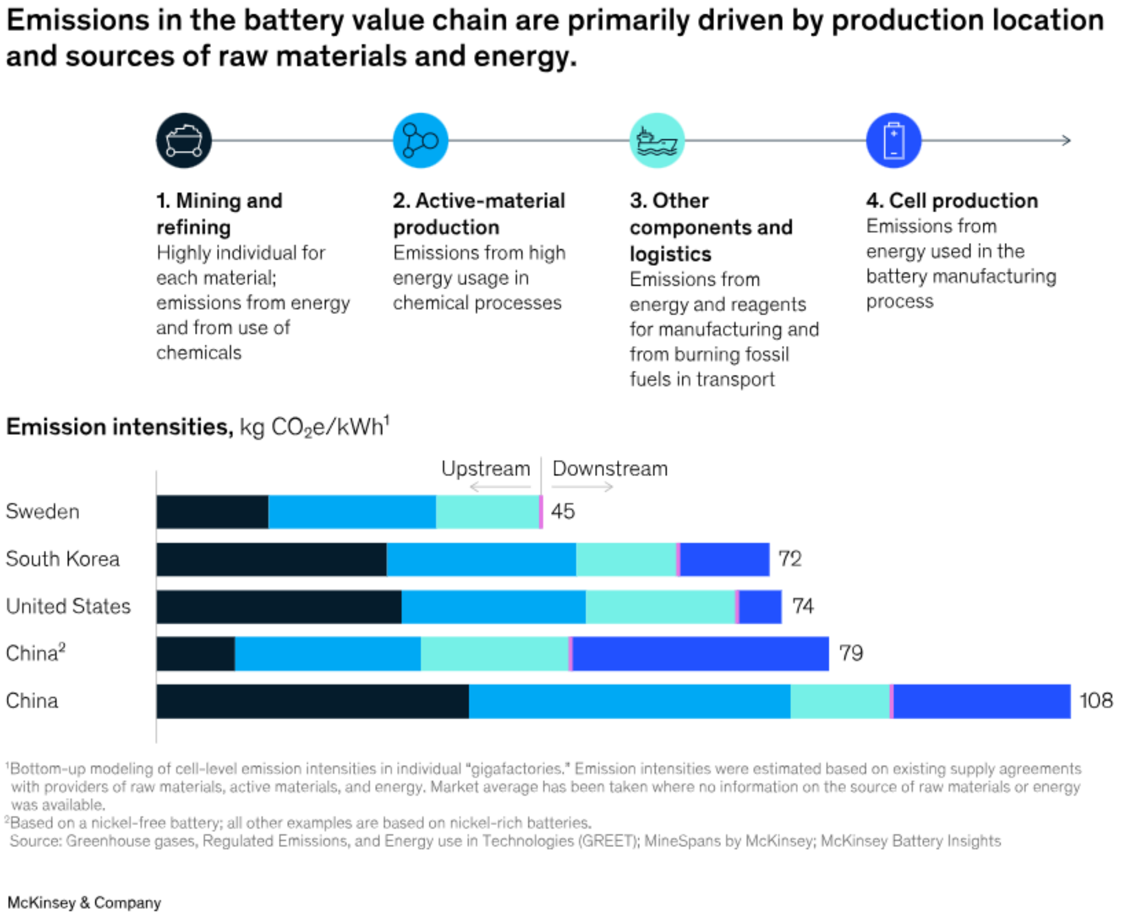
(a) Minimum: 45 kgCO_2eq/kWh battery capacity – This represents the lowest value we encountered in our research and corresponds to the CO_2 emissions of a battery manufactured in Sweden (see McKinsey & Company (2023))

(b) 75 kgCO_2eq/kWh battery capacity – This corresponds to the CO_2 emissions of a battery manufactured in the USA (see McKinsey & Company (2023)). Dai et al. (2019) were able to analyse real data from a Chinese cathode manufacturer and calculated an average emission value of 73 kgCO_2eq/kWh for a NMC11 battery.

(c) 110 kgCO_2eq/kWh battery capacity – According to McKinsey & Company (2023), this corresponds to the CO_2 emissions of a battery manufactured in China that contains nickel in its composition. Popien et al. (2023b) also refer to a number of lithium-ion batteries in this range (e.g. NCA, NMC622). The authors assume that material production and component production take place in China, while the battery cell itself is manufactured in Germany.

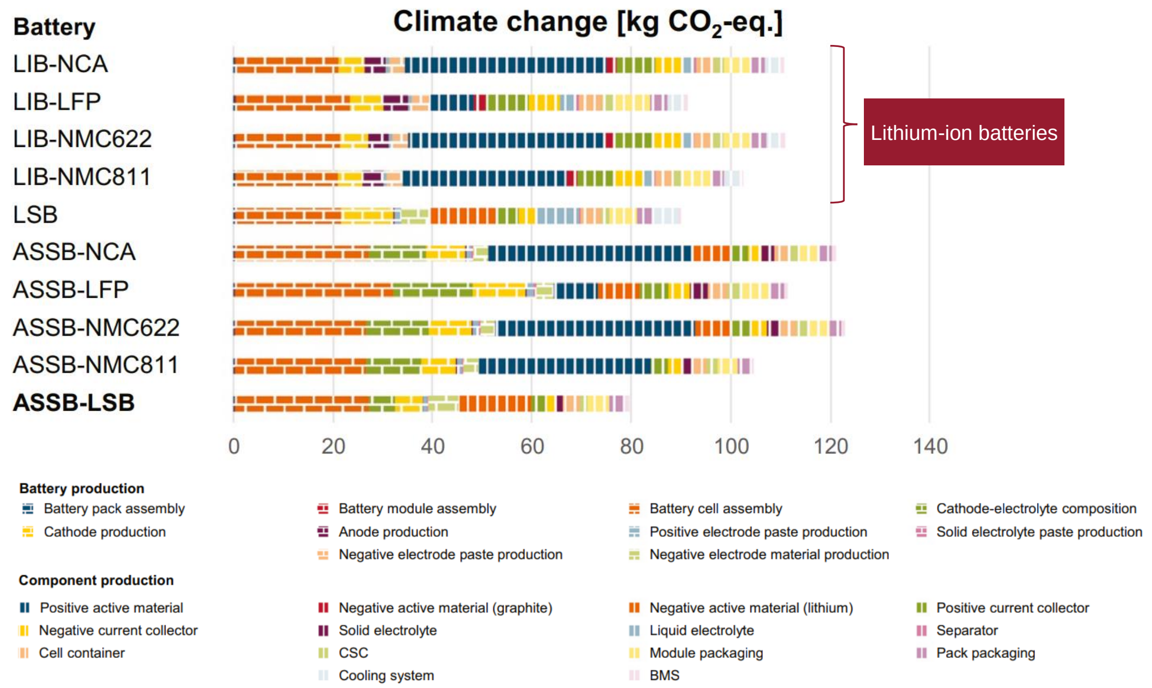
(d) Maximum: 140 kgCO_2eq/kWh battery capacity – According to a recent study, this corresponds to the current carbon intensity of the production of NCA and NCM lithium-ion batteries in China and is regarded as the maximum value for the emission intensity of battery production (see Lai et al. (2023)).

Figure 9 Comparison of CO_2 emissions in battery production between different countries



Source: McKinsey & Company (2023)

Figure 10 Comparison of CO_2 emissions in battery production between different battery types manufactured in China



Source: Popien et al. (2023)
Note: [Insert Notes]