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

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Study commissioned by:

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SUMMARY

In the context of the Paris Climate Agreement, Germany and the European Union have set themselves ambitious goals for reducing greenhouse gas emissions ("GHG emissions") by 2050. This goal requires ambitious CO_2 reduction strategies in all sectors that consume energy. This includes the road transport sector, whose GHG emissions have recently attracted much political attention. Despite increasingly efficient vehicles, growing demand for mobility has meant that it has not been possible to reduce GHG emissions in the transport sector since 1990. Against this backdrop, a fierce debate around energy policy has begun with respect to which concepts and technologies can be used in road transport to achieve a massive and long-term reduction in CO_2 emissions.

This study aims to investigate the climate impact of various types of drive over the entire lifespan of the vehicles, with a focus on battery electric vehicles and vehicles with combustion engines (using modern-day fuels and the inclusion of "green" e-fuels). At the centre of this is a comparison between the two options of "renewably generated charging current" and "renewably generated liquid fuels". In this context, we will look at the current situation as well as future scenarios in which the provision of drive energy will become increasingly green, both on the side of electricity and on the side of liquid fuels.

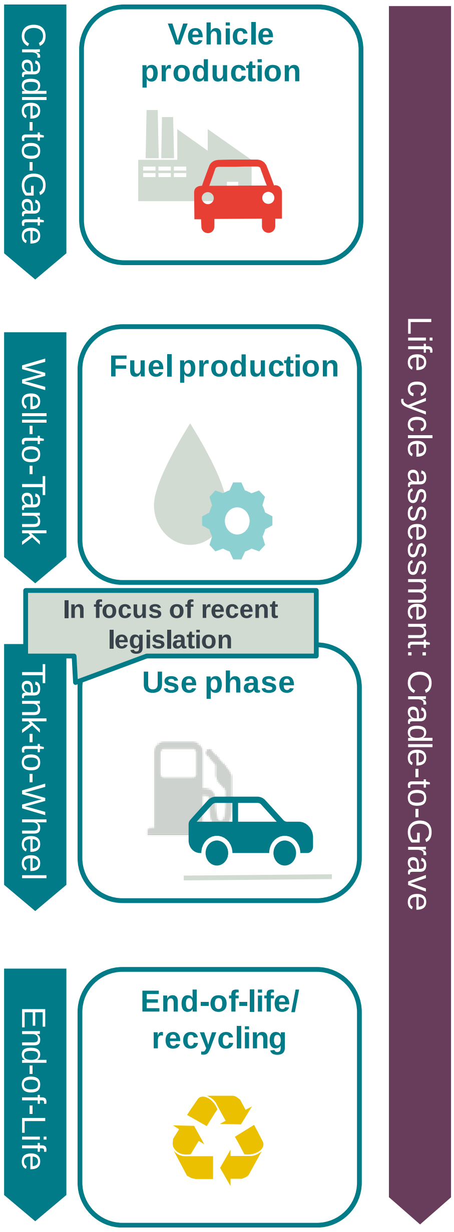
The study and the associated calculation tool (Excel model) highlight cause-and-effect relationships and results that are intended to add transparency and comparability of technological approaches to reducing life-cycle CO_2 emissions. This provides a basis for easier development of technologically sound and robust strategies.

The results can be summarised as follows:

CO_2 savings in transport can be achieved in various ways

One lever is the conversion of vehicles to fuel-efficient drives such as battery electric vehicles (BEV) or highly efficient combustion engines (ICEV - internal combustion engine vehicles). Another lever is the switch from fossil to climate-neutral drive energies such as green electricity for charging or liquid fuels (e-fuels) generated from renewable energies.

Figure 1. Comprehensive LCA considers all life cycle stages



Source: Frontier Economics

However, a narrow perspective (a focus on direct rather than system wide-emissions) and political regulations pose challenges for technological diversity

In some areas of policy, especially surrounding passenger transport (passenger cars), BEVs are regarded as the technological solution of choice for reducing CO_2 emissions. In the current public debate, battery electric vehicles are regarded as emission-free since no CO_2 emissions are produced directly from using the vehicle. In contrast to this, vehicles with a combustion engine (ICEV) always produce CO_2 emissions when used. Where this system or accounting limit, that looks only at directly use-related emissions (tank-to-wheel), is applied, a battery electric drive has a clear advantage over a combustion engine drive in terms of the CO_2 impact. As a result, various climate policy decisions both in Germany and at EU level are currently one-sidedly orientated towards battery electric vehicles.

A comprehensive life cycle analysis forms the basis of robust strategies and sustainable concepts

In the restricted tank-to-wheel scenario outlined above, only one section of the life cycle – the use of the vehicles – is considered. To consider and evaluate technology options as comprehensively as possible in terms of their effects on the climate, however, the perspective needs to be extended towards a comprehensive (cradle-to-grave) life cycle analysis (**Figure 1**). In this case, the generation of drive energy and the disposal or recycling of the vehicle are taken into account alongside the mere use phase. Further, not only emissions associated with the production of a vehicle in Germany or the EU are considered, but also in supplying countries such as China. In our study, we calculate life cycle emissions exemplary for four segments of vehicles – three car segments (compact, medium-sized and SUV) and the lightweight commercial vehicle segment (LCVs).

A bird's eye view already reveals new findings

Taking into account all life cycle stages, the CO_2 emissions of a BEV are unexpectedly high. Mostly, the very energy-intensive production of batteries is responsible for the CO_2 emissions, but so is the generation of electricity for charging , that is produced with a high share of fossil fuels in many places. Adding to this is the fact that CO_2 emissions are nowadays to a considerable degree "exported" from Germany and the EU to third-party states. The production of batteries for medium-sized vehicles generates GHG emissions of more than 9 t of CO_2 when the batteries are produced in China, for example. With these emissions alone – before a BEV has even been driven a single mile – medium-sized vehicles with diesel drive can travel around 56,000 km using today's fossil fuels.

Figure 2 Many influencing factors determine the overall CO_2 impact in individual cases

Vehicle type
Year of acquisition
Operating lifetime in years
Annual driving distance, km
Battery capacity, kWh (tank size)
Fuel
Progression of electricity mix
Operating country
Electricity mix in operating country
Production country of battery
Electricity mix in production country of battery

Source: Frontier Economics

Note: The cause-and-effect relationships of these and other influencing factors can be analysed in the calculation tool.

A comparison of the climate impact of BEVs and ICEVs over the entire life cycle reveals that the differences are relatively small in many cases and that, in fact, no one technology is superior. Instead, many different factors can determine the overall CO_2 impact in each case. The most important factors, alongside the electricity and energy mix of the manufacturing and operating countries, are, for example, a vehicle's size, its range and its lifetime mileage**(Figure 2**). The following trends can be observed with respect to the climate impact:

- **ICEVs have an advantage** for larger vehicles and over longer ranges: as a result of the energy-intensive battery production process, the BEV starts out with a heavier "CO_2 burden" than the ICEV. As the size of the vehicle and its range increase, so too does the size of the required battery, with corresponding impacts on the CO_2 emissions during battery production.
- **BEVs have an advantage** under longer lifetime mileages: The production of electricity for charging for BEV operation is currently – and for the foreseeable future – associated almost all over the world with CO_2 emissions. In many cases, however, battery electricity emissions are overall lower than the emissions that are produced from the use of fossil fuels in an ICEV. In these cases, a BEV can compensate for the higher manufacturing emissions compared to an ICEV when driven up to a high mileage during the use phase.

In the future, too, both ICEVs and BEVs are technology options for sustainably reducing CO2

In future, both BEV and ICEV have the potential to contribute towards achieving climate targets. Not only does the increasingly renewable energy-based production of vehicles play a decisive role here, but so too does the provision of renewable energy-based drive energy. The CO_2 footprint of ...

- ... BEVs can be reduced in the future if electricity from renewable energies is used for battery production and the CO_2 intensity of the electricity for charging is reduced.
- ... ICEVs can be significantly reduced in the future by using more bio-fuels and especially synthetic fuels, made from renewable energies and therefore climate-neutral (e-fuels), instead of the fossil fuels (with small amounts of bio-fuels added) used currently.

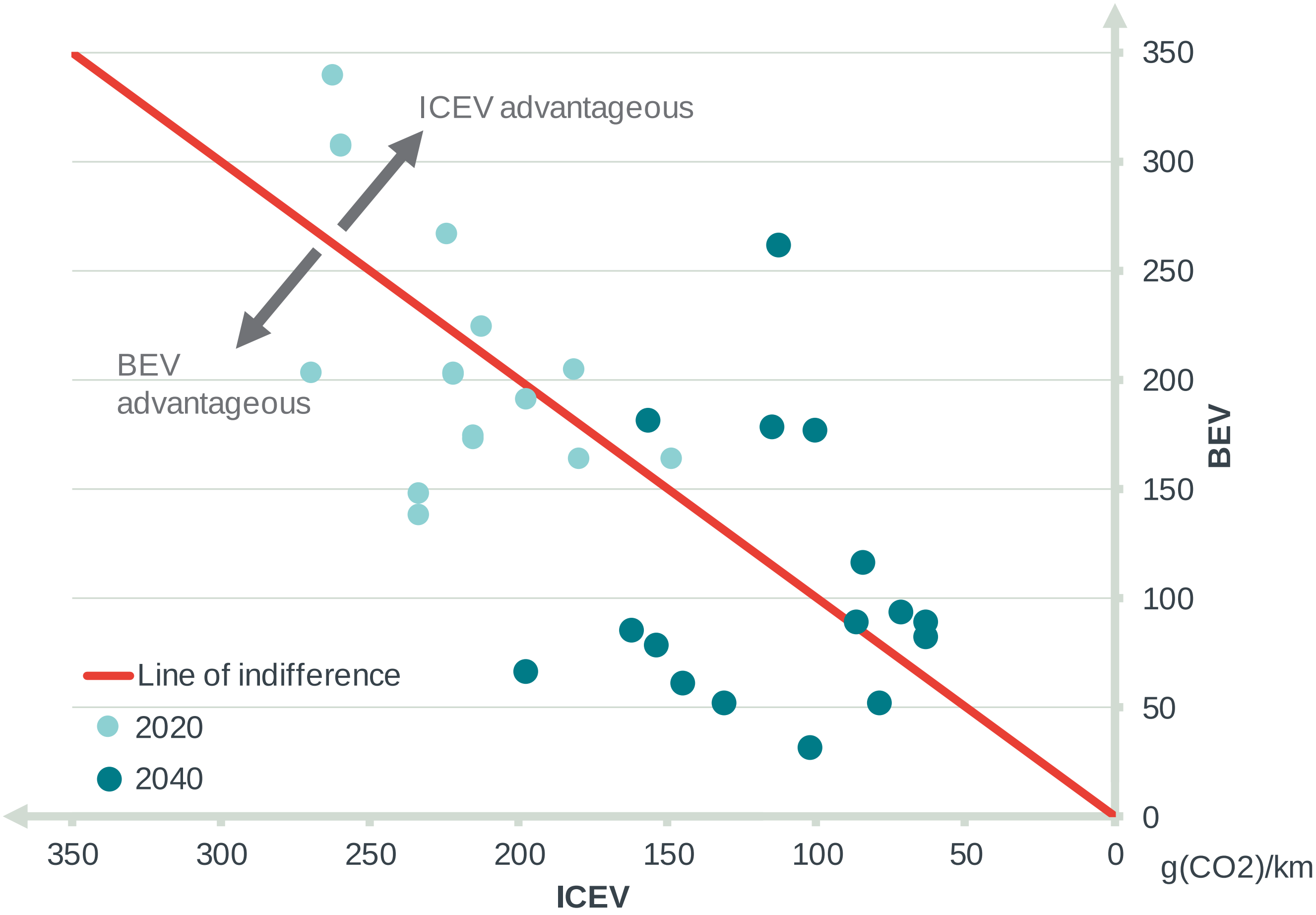
Blending-in e-fuels (for ICEV) and the increasing generation of production and battery charging electricity from renewable energies (for BEV) are therefore both options for reducing CO_2 in the transport sector. Maintaining a wide variety of vehicle types and drive technologies also offers the potential to meet the various mobility requirements in the future without compromising climate protection targets or practical reliability. The respective areas of application are diverse:

- **BEVs** offer a good prospect for lighter passenger cars on shorter distances in regions with an easily expandable charging infrastructure (e.g. also for light commercial vehicles used over short distances).
- **ICEVs**, with the growing use of e-fuels, are ideal for cars with high performance requirements (such as from the medium-sized class upwards) or in the case of LCVs with higher technical demands (range, cargo).

Figure 3 shows how the use of a variety of technology options can also make sense from the perspective of climate policy. The figure shows the average CO_2 emissions (g (CO_2)/km) over the life cycle of various vehicle types with various sizes, ranges, lifetime mileages, production and operating countries for 2020 and 2040. For the longer term, we have assumed both a greener electricity mix for the electricity for charging used in BEVs (average CO_2 intensity between 2040 and 2050 at 82% in the reference case in the EU, for example) and an increasing blending share of e-fuels (average 70% in the period from 2040 to 2050). Points above the red line indicate advantages of ICEVs regarding the climate impact, while points below the line indicate advantages of BEVs.

So, comparing the climate impact between BEVs and ICEVs, it is apparent that differences are relatively small in many cases, and that the overall CO_2 impact varies from case to case.

Figure 3. Climate impact advantages of ICEVs and BEVs vary between application cases in the short and long term as electricity and fuel mix become "greener"



Source: Frontier Economics

Note: The figure compares the emissions of otherwise structurally identical vehicles with battery drive and combustion engine drive for various analysis sensitivities. The vehicle type, the duration of use and the annual performance, the country of operation and production, as well as the assumptions regarding the future development of the electricity and energy mix, were all varied.

"Green" synthetic fuels are also suitable as a medium-term measure since they can be used without technical modifications to the vehicle fleet both in Europe and in parts of the world where the comprehensive use of BEVs is still a long way off due to a lack of infrastructure. The handling and use of e-fuels are relatively simple, and their use will become virtually indispensable from today's perspective for some applications that are outside the scope of the areas covered by this study (such as aviation).

From the point of view of climate policy and regulation, a move towards technological open-mindedness is required

The examined climate impacts of drive technologies in the field of cars and LCVs have shown that a mix of technologies is preferable to a limited choice of technologies that is determined from the outset. To reduce CO_2 emissions in the long term, a sensible and recommendable move would be to design the regulatory frameworks such that not only battery electric drives but also drives based on e-fuels (ICEV) are promoted on an equal footing. The following steps are required for this (see **Figure 4**):

Figure 4. The next steps are crucial

Bird's eye view	Technologies have to be consequently viewed from a bird's eye, not from a worm's eye
Technology mix	Abstain from focus on specific technologies – climate policies must enable and promote a technology mix that is in line with the objective
Fair regulations	Fair and technology-open regulatory frameworks have to be implemented as soon as possible.
e-fuel support	National support programs are to be opened for e-fuel initiatives
Overall strategy	Innovations on drivetrain technologies and fuels need to be imbedded into an overall strategy of transport–related policies
Global climate change	Transport and climate policies have to be thought of from a global perspective

Source: Frontier Economics

1. PURPOSE AND BACKGROUND TO THE STUDY

80-95%

reduction in CO_2 emissions compared to 1990 by 2050

is the ambitious goal of the 2050 climate protection plan in Germany which requires CO_2 reductions in all sectors – including road transport

0 g (CO_2)

per km travelled:

BEVs are only emission-free nowadays from a limited perspective

Background: The Paris Climate Agreement defines global greenhouse gas neutrality after 2050 – with a massive reduction in GHG also required in the transport sector.

With the Paris Climate Agreement, the global community has set itself the goal of achieving GHG neutrality over the course of the second half of this century. The European Union is striving to achieve GHG neutrality by as early as 2050. With its 2050 Climate Protection Plan,[1] Germany has set itself the goal of reducing greenhouse gas emissions by 80% to 95% compared to 1990 by 2050. These goals require ambitious CO2 reduction strategies in all sectors that consume energy, including the transport sector.

GHG emissions in road transport in particular have recently drawn political attention. Despite more efficient vehicles, CO2 emissions from road transport continue to remain at a similar level to 1990 in Germany. At EU level, emissions from the transport sector have actually risen. The reasons for this are primarily the increased amount of traffic in the freight transport sector and a constantly growing demand for individual mobility.

Against this backdrop, a fierce debate around energy policy has sparked regarding concepts and technologies in road transport that can achieve a massive and long-term reduction of fossil fuels and therefore CO2 emissions.

Battery electric vehicles (BEVs) are regarded in some areas of policy as the technological solution of choice for reducing CO_2 emissions, especially for passenger transport (cars). In the general current debate, battery electric vehicles are regarded as free of CO_2 emissions. This widely held view is based on the fact that there are no directly use-related CO_2 emissions, i.e. at the point at which final energy (electrical energy) is converted into useful energy (mechanical movement).

1 2050 Climate Protection Plan – Climate protection policy principles and targets of the federal government, https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf

LCA

Life cycle assessment

provides information on the overall CO_2 impact of drive technologies.

In contrast, vehicles with a combustion engine (ICEVs) always produce CO_2 emissions in this energy conversion stage. IHere the liquid fuel available in the fuel tank represents the final energy, which is then converted into useful energy (mechanical movement).

Where this system or accounting limit (tank-to-wheel) is applied directly to the vehicle, the battery electric drive always has a clear advantage over the combustion engine drive in terms of the CO_2 impact.

In our study we examine to which extend this narrow system limit on directly use-related emissions is effective and which emissions result from an approach that considers all life cycle stages of a vehicle.

Objective: Analysis of the CO2 impact of various vehicle drive systems over the entire life cycle (LCA – life cycle assessment) today and in the future

Against this backdrop, the UNITI Bundesverband mittelständischer Mineralölunternehmen e. V. has asked Frontier Economics to examine the climate impact of various types of drive technologies over the vehicles' entire life cycle. This study and the associated calculation tool (Excel model) highlights cause-and-effect relationships and results that are intended to add transparency and comparability of possible technological solutions concerning CO_2 emissions over the life cycle. Developing technically sound and robust strategies is easier on this basis.

This study report focuses on the following areas of content:

- **Section 2** illustrates fundamental solutions for sustainably reducing CO_2 in road transport, the current status of the energy policy discussions and particularly highlights the limits of the key analytical and regulatory approaches that are currently used.
- **Section 3** explains the principle of life cycle assessments (LCA) which – at least among experts – are being used more and more (from the tank-to-wheel towards the cradle-to-grave perspective).
- With the aid of selected practical case studies, **Section 4** explains that, based on LCA already today and for the foreseeable future, no drive technologies are generally dominant over other technologies in terms of CO_2 emissions; this is also true for battery electric vehicles versus combustion technologies. Much rather, the advantage of technologies regarding CO_2 emissions depends on a range of factors, and therefore on the individual application case.
- **Section 5** considers drive technologies given the growing use of renewable energies both for e.g. the production of electricity and

of batteries and for the provision of liquid fuels through the blend-in of green, synthetic gasoline and diesel.

- **Section 6** summarises the conclusions derived from this study and sets the results in a wider energy policy context that extends beyond the accounting of CO_2 emissions.

On the basis of the findings of the LCA this study formulates recommendations for political action . The study therefore intends to promote the debate regarding future solutions for reducing CO_2 emissions in the transport sector.

The study is supplemented by a calculation tool that enables the user to determine the CO_2 impact of vehicles based on assumptions for all influencing parameters and scenarios. The model can also be used for a sensitivity analysis of various parameters, i.e. for an analysis on how parameter variations affect the vehicles' CO_2 impact over the whole life cycle as well as in the separate life cycle stages.

2. THE PUBLIC VIEW OF SOLUTIONS FOR REDUCING CO_2 IN ROAD TRANSPORT IS STILL LIMITED

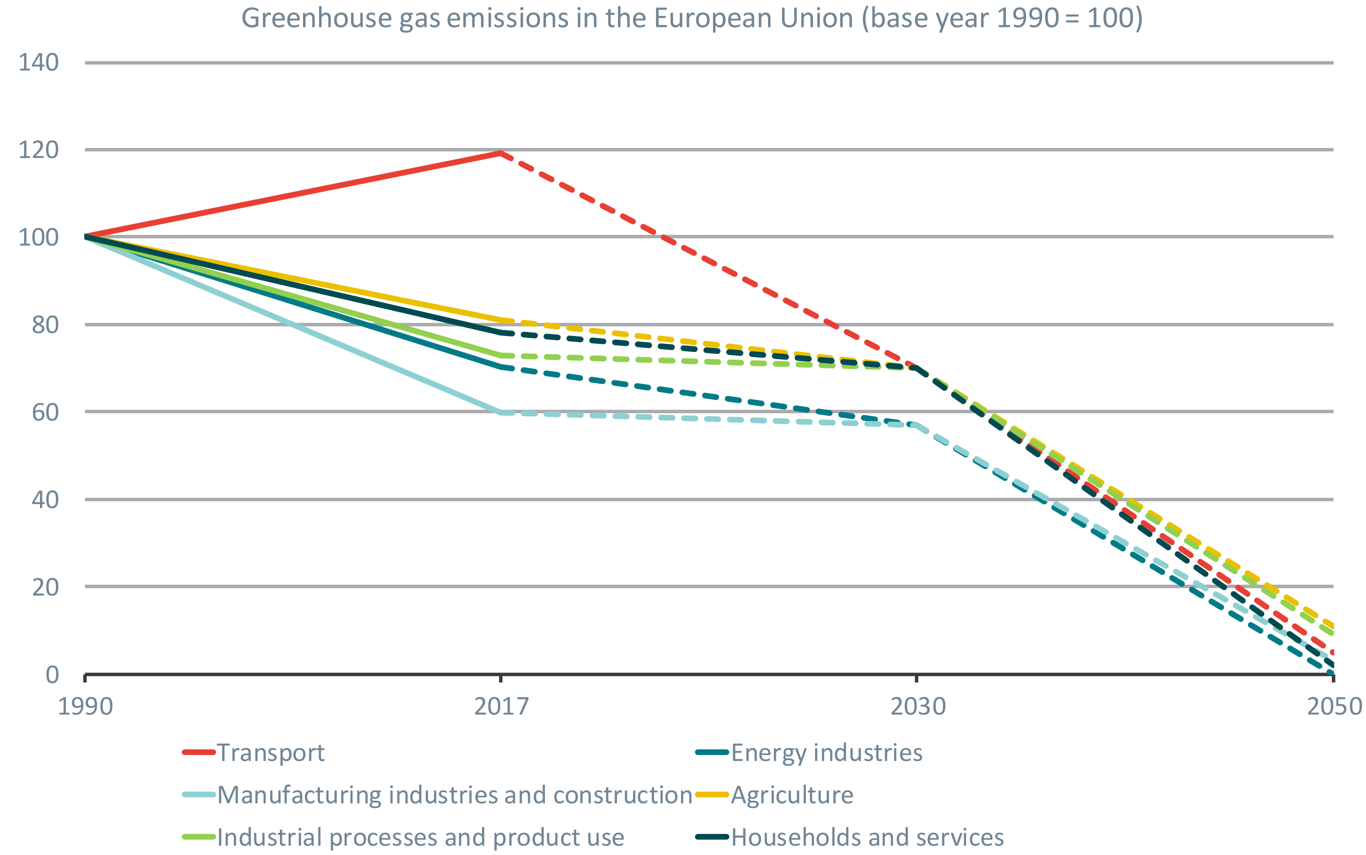
To achieve the climate goals, sustainable solutions for reducing CO_2 in road traffic are essential. This section explores the current situation in the transport sector regarding CO_2 emissions, as well as the challenges around climate policy. We examine different possible solutions and regulations to assess whether they allow the various technologies to contribute to CO_2--avoidance.

2.1 Achievement of the climate protection goals requires massive reductions in CO_2 emissions, including in road transport

The transformation of the energy system in Germany requires a massive medium-term to long-term reduction in greenhouse gas emissions in all sectors that consume energy.

This requirement also includes road transport which, like the entire mobility sector, has seen stagnating emissions in Germany over recent decades and even rising emissions in Europe since 1990 (cf. **Figure 5**).

Figure 5. In the European mobility sector, reductions in CO_2 emissions need to be accelerated in order to achieve the 2050 climate protection goals



Source: Frontier Economics based on Eurostat, Greenhouse gas emissions by source sector.
Note: Baseline year 1990 = 100.

31%

lower = CO_2 emissions per km driven

today compared to 2000

however at the same time with a significant rise in traffic

This rise is primarily due to the increased demand for individual mobility and the increasing transport of goods by road within the domestic EU market. Despite this, efforts to reduce CO_2 in the transport sector were considerable: Between 2000 and 2017, the average CO_2 emissions per kilometre of a purchased new car in the EU were reduced by 31%[2] thanks to efficiency improvements. These efficiency improvements, however, have been more than offset by the overall rise in traffic volume.

Against this backdrop, a fierce energy policy debate has sparked on which road transport concepts and technologies can and should contribute to reducing CO_2 emissions in Europe and Germany.

[2] Cf. https://www.eea.europa.eu/data-and-maps/daviz/average-emissions-for-new-cars-4#tab-chart_1

2.2 The current car fleet with its modern drive technologies primarily uses liquid fuels

99.7%

of cars

today in Germany are equipped with combustion engines

Concepts and technologies for reducing CO_2 emissions in road transport are not planned and implemented on a "green field", but instead are faced with the current vehicle fleet and existing transport infrastructures. As such, it makes sense in terms of future strategies for passenger transport to consider the current situation in the transport sector.

The current technology mix for the car sector in Germany consists of... [3]

- ... 99% vehicles with an internal **combustion engine** (ICEV). Liquid fossil fuels such as diesel and gasoline based on mineral oil are mostly used nowadays for drive energy.[4]
- ... 0.2% **battery electric vehicles** (BEV) . Their batteries are charged with electricity and the BEV is driven by an electric motor. The charging current is at present mostly generated from fossil-based energy. In Germany, renewable energies account for around 38% of the energy mix in generation.[5]
- ... less than 0.1% **fuel cell electric vehicles** (FCEV). FCEVs are electrically powered vehicles whose drive energy is generated in a fuel cell from the chemical reaction between hydrogen and an oxidising agent. The hydrogen used nowadays is primarily obtained from natural gas and is therefore not climate-neutral (hence the term grey hydrogen).
- …and 0.7% **other forms of drives** such as hybrid variants of the drives mentioned above or vehicles with other or gas drive technologies (CNG, LNG).

The current dominance of liquid fuels both in Germany and internationally is due to their technical and chemico-physical properties. Due to the high energy density relative to their volume, compared to all other energy sources available today liquid fuels offer:

- a high degree of flexibility in use – in all vehicle classes from cars to heavy goods vehicles.

[3] The figures are based on data from the Federal Motor Transport Authority as of 1 January 2019, see https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/bestand_node.html

[4] Gaseous fuels such as natural gas and hydrogen – currently mainly produced through fossil natural gas ("grey" hydrogen) – can also be used in combustion engines.

[5] Cf. Federal Environment Agency, https://www.umweltbundesamt.de/presse/pressemitteilungen/bilanz-2018-anteil-erneuerbarer-energien-steigt-auf.

Liquid fuels

have strengths in application technology due to their high energy density and easy handling

- excellent transportability – especially where there are long distances between generation and final use.
- good storage capability with a high energy storage capacity.
- simple and virtually hazard-free handling at atmospheric ambient temperatures and pressures without cumbersome process technology.

These aspects, however, are offset by the carbon dioxide content of the waste gases produced during combustion. Based on this situation, from a climate policy perspective the question arises how the mobility sector can be designed in a way that enables the achievement of the climate goals – ideally without restricting the increasing mobility demanded by the population and business.

2.3 CO_2 savings in transport can be achieved in a variety of ways and make sense

Against this backdrop, there are various technical options available for reducing CO_2 emissions to the required extend:

- **Switch to vehicles with fuel-efficient drives:** All things being equal, more efficient drives save CO_2 emissions through the more efficient use of a fuel. This includes a) highly efficient combustion engines, b) electric engines and c) fuel cells.
- **Switch from fossil to climate-neutral drive energies:** These include:
  - **Renewably produced electricity for charging:** This can be used in battery electric vehicles.
  - **Renewably produced liquid fuels:** Conventional diesel and gasoline fuels can be replaced gradually with bio or e-fuels. While bio-fuels are based purely on the conversion of biomass[6], e-fuels are synthetic fuels that are produced from water and carbon by using electricity. If only regeneratively generated electricity is used, however, and the carbon has previously been extracted from the atmosphere, for example, e-fuels are classified as completely climate-neutral[7] fuels.
  - **Renewably produced "green" hydrogen:** While "grey" hydrogen is produced from a steam reforming process involving natural gas and therefore causes emissions during

[6] The cultivation of plants solely for energy production is however controversial in many respects. The argument that "energy plants" compete with the cultivation of food is generally put forward first by critics.

[7] From an overall balance perspective, synthetic fuels and combustibles can be produced in a climate-neutral manner and burned again: although the end use generates CO_2 emissions, this CO_2 is taken out of the environment during production. The climate impact is therefore in equilibrium and harmful environmental effects are reduced to virtually nil.

production, hydrogen can also be produced in a climate-neutral way. Green or renewable hydrogen is produced using renewable electricity and the electrolysis method.

- **Renewably produced methane** (through the methanisation of renewably produced hydrogen and carbon).

In our study, we contrast the options of "renewably generated electricity for charging" and "renewably generated liquid fuels". We therefore in particular contrast the CO2 emissions along the life cycle of battery electric vehicles, which are currently often the subject of political debate, with those of vehicles driven by combustion engines that run on liquid fuels. The latter offer the advantage of being able to build on existing supply infrastructures and not requiring any changes in use.[8]

In this context, we look at the current situation as well as future scenarios in which the provision of drive energy will become increasingly greener, both on the electricity side and on the side of liquid fuels, in accordance with the strategies outlined above.

> Despite the variety of potential solutions for reducing CO_2, the political regulations currently focus virtually entirely on BEVs

2.4 Technological diversity meets narrow political regulations

Despite the diverse technological approaches for implementing the ambitious climate and CO_2 reduction goals in the transport sector, it is primarily the battery electric vehicle - especially for passenger transport (usually cars) but in some cases also for buses and heavy goods transport - that is in political circles widely regarded as the only technological solution for reducing greenhouse gas emissions. Other options, such as switching from renewable energies to synthetically produced fuels, have so far been dealt with as subordinate in discussions.

One reason for the political focus on BEVs as the solution of choice could be that BEVs, unlike ICEVs, are generally perceived by politicians to be free of CO_2 emissions. This can be seen in various policy announcements and regulatory frameworks, both at European and national level:

- Among the **EU emission reduction targets for passenger cars** and light commercial vehicles, the target of an average maximum of 95 g (CO_2)/km per vehicle within a car manufacturer's vehicle fleet will apply from 2021 (EU fleet targets[9]). Among the measurement targets, BEVs are recognised as emission-free, while for many ICEVs it is practically impossible to achieve these targets. This is especially

[8] For hydrogen and methane too, the transport sector still needs substantial infrastructure to be built, which is why we are focusing in this study on liquid fuels as an alternative to battery electric vehicles.

[9] Cf. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

also true since the use of bio-fuels and synthetic fuels produced from renewable energies cannot be counted towards the quotas, or only insufficiently so.

- The **coalition agreement**[10] between the CDU, CSU and SPD primarily makes mention of support for electromobility and the establishment of an electricity charging infrastructure in the context of solutions for the mobility sector. A test route for battery electric trucks in combination with overhead electricity lines on the A5 motorway has already been set up, for example, and one on the A1 is in preparation. Without doubt the establishment and expansion of the charging infrastructure and the promotion of electromobility can make a contribution towards reducing CO_2 emissions in the transport sector, however alternative technologies are often overlooked. The unilateral focus on electromobility is therefore being amplified by the current coalition agreement.

> Pioneering regulations and political announcements in the EU today are centred around just one technology.

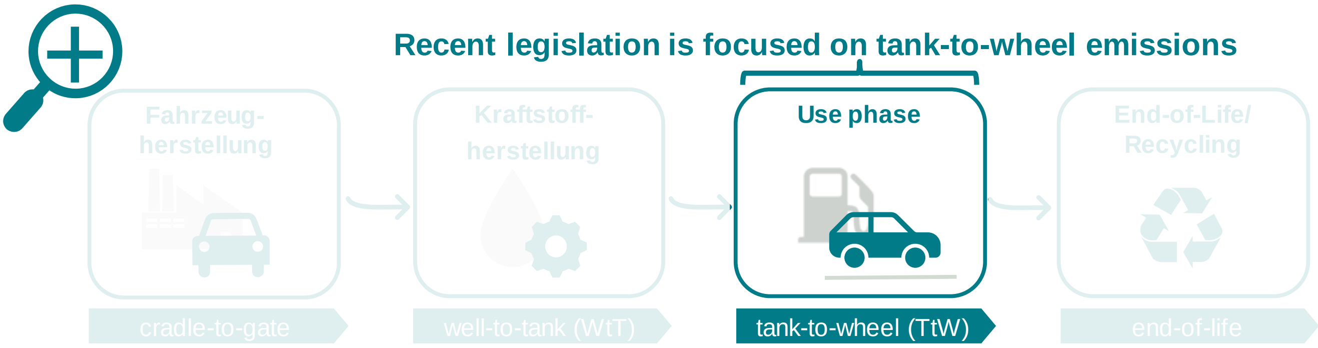
- Some European countries currently call **new ICEV registrations into question** in the medium- to long-term, such as in Norway, Ireland or Denmark. Norway aims to have a fleet of new cars without a single combustion engine from 2025 onwards. Ireland, Denmark and Sweden pursue this goal for 2030, while the UK and France aim for 2040. Financial incentives are also set to encourage people to buy BEVs.

The reasons why the regulations and political announcements at European level focus on the supposedly emission-free BEV (cf. **Figure 6**) could be these:

- the widely held belief that BEVs are emission-free is based on the fact that there are no drect use-related CO_2 emissions, namelyat the point at which the final energy (electrical energy) is converted into useful energy (mechanical movement and other consuming units).
- In contrast to this, combustion engines always produce CO_2 emissions during this energy conversion stage. Here, the liquid fuel available in the fuel tank represents the final energy which is then converted into useful energy (mechanical movement and other consuming units).

[10] Cf. coalition agreement between the CDU, CSU and SPD, 19th parliamentary term (2018), p.14 https://www.bundesregierung.de/resource/blob/975226/847984/5b8bc23590d4cb2892b31c987ad672b7/2018-03-14-koalitionsvertrag-data.pdf?download=1

Figure 6. European policy and regulatory frameworks currently focus on tank-to-wheel emissions impacts



Source: Frontier Economics

Consequently, when defining the narrower "tank-to-wheel" system limit, battery-electric drive always has a clear advantage over the internal combustion engine in terms of CO_2 emissions. This definition has so far failed to take into account the following circumstances, however:

- if the entire life cycle (cradle-to-grave) is considered, then significant amounts of greenhouse gas emissions are produced even by BEV, especially during the battery production process and the and generation of electricity for charging.
- The questions around raw materials and disposal of components (e.g. batteries) have still not been fully explored. Energy-intensive battery recycling could become increasingly necessary.
- The CO_2 impact of an ICEV could be improved significantly, for example with the use of synthetic fuels.

Therefore a wider perspective on technology options that are generally available on the way towards greenhouse gas neutrality seems necessary.

3. THE CHANGE FROM THE GROUND-UP TO THE BIRD'S EYE PERSPECTIVE HAS BEEN STARTED AND IS MAKING PROGRESS

In the previous section, we explored the various options for avoiding CO_2 emissions in road transport, whereby transport policy strategies for climate protection are focusing heavily on the electrification of transport. We have also found that the rationale for focusing on electrification is based on a very limited view on CO_2 emissions caused by vehicles or drive technologies, namely directly use-related emissions from the vehicle's tailpipe itself.
In this section, we will widen our perspective and take a more comprehensive view with the concept of the life cycle analysis. On this basis, the risk of one-sided strategic mistakes and misdirection in the transport sector, which are usually associated with very costly corrections, can be reduced. This type of comprehensive approach is also recommended for the strategic orientation of the transport sector in the context of the defined GHG reduction targets.

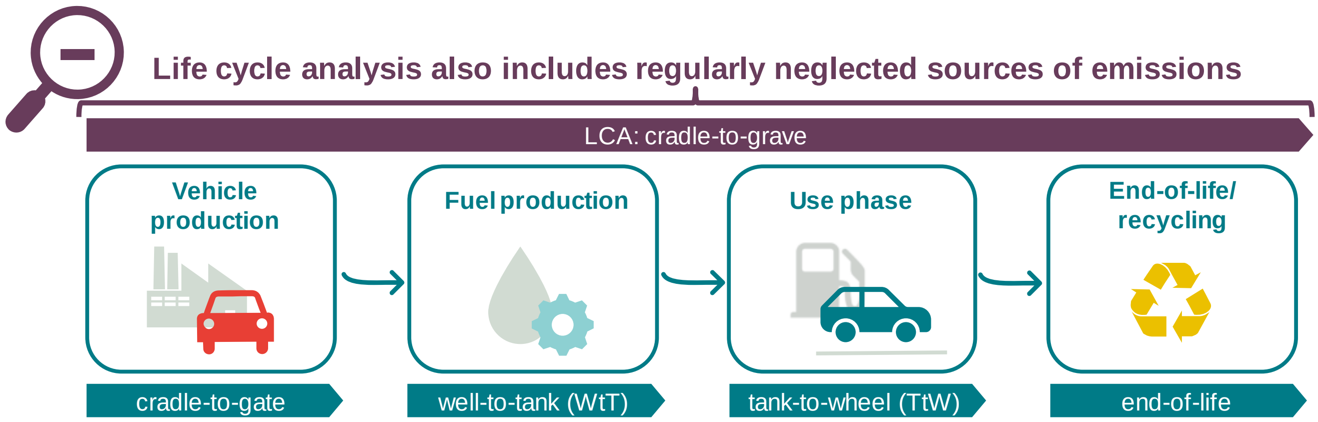
3.1 A comprehensive life cycle analysis forms the basis for robust strategies and sustainable concepts

The aim of a comprehensive technology analysis is to consider and evaluate technology options in as complete a manner as possible in terms of their impacts on climate and the environment. A comprehensive life cycle analysis considers the following areas:

- **Life cycle stages:** All of a vehicle's life cycle stages are included (**Figure 7**). Not only are the CO_2 emissions that are generated by combusting fuel while driving on the road taken into account, but so are the emissions produced while generating the drive energy, for example.
- **Time component:** Aspects that vary with time must also be measured in a variable way. The CO_2 intensity of the energy sources, for example, changes over the years of use depending on the proportion of energy produced from renewable sources.
- **Geographies:** Individual life cycle stages for the vehicle in question (especially production and use phase) can occur in different geographical regions with different compositions of the electricity and energy mix. A comprehensive approach includes CO_2 emissions across national and regional borders. Batteriy production is currently very energy-intensive, and therefore high

CO_2 emissions, outside of Europe and then exported to Europe (see below). The emissions are then accounted to the supplying country outside Europe, while the product – the batteries – are used by consumers in Europe. This "export" of CO_2 emissions to other regions of the world makes Europe's CO_2 footprint look better, but it is counter-productive for climate protection. Life cycle analyses consider these effects.

Figure 7. Comprehensive analysis approach factoring all of a vehicle's life cycle stages into the CO_2 impact



Source: Frontier Economics

With the LCA approach for vehicles (in this study passenger cars and light commercial vehicles), the use phase limited accounting is extended by the following, system-inherent life cycle stages (see **Figure 8**):

- **Vehicle production (cradle-to-gate)**: In our analysis we focus on the CO_2 emissions generated by producing the components of the various drive systems and bodywork, as well as generalised other vehicle components such as vehicle fittings. Regarding BEVs, the production of the battery in particular generates CO_2 emissions due to the
  - relatively energy-intensive battery production process and
  - the use of electricity from renewable, but also fossil-based, sources. Today, battery production takes place mainly in

Asia (approx. 85% of production capacity is based in China, Japan and South Korea[11]).

486 g (CO_2)/kWh

was the average CO_2 emission-intensity of the electricity mix in Germany in 2017[12]

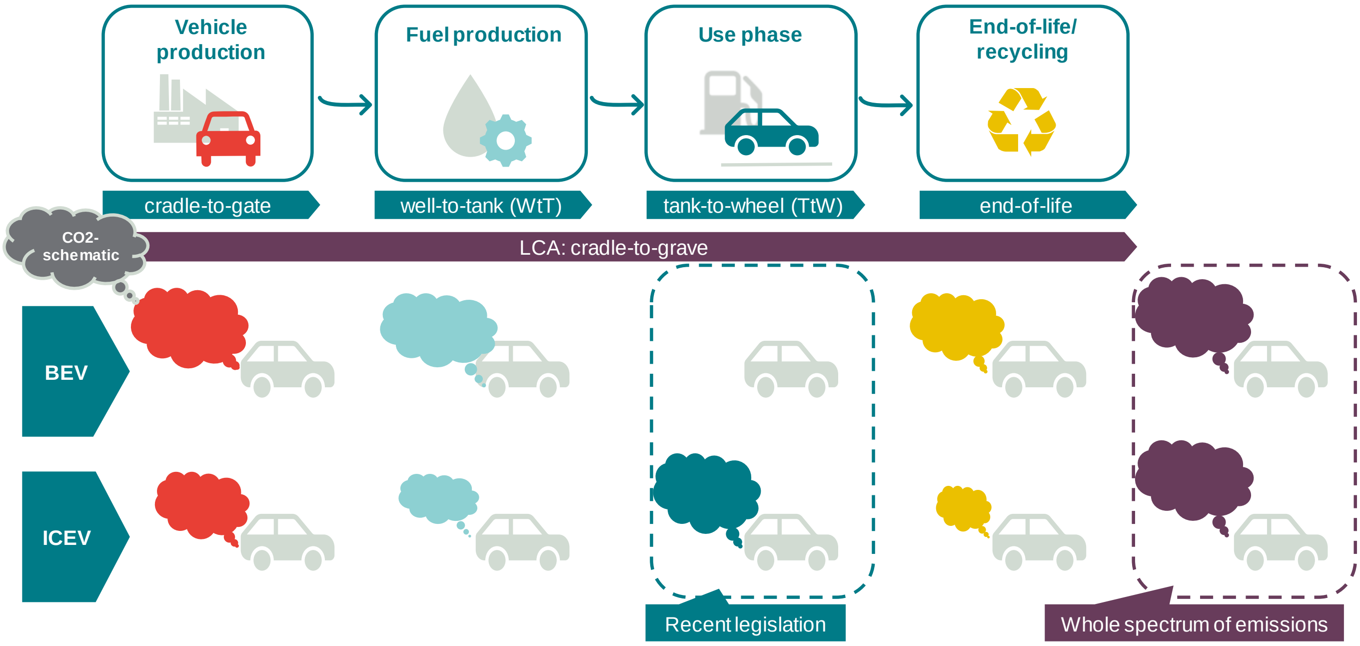
- **Generation of drive energy (well-to-tank):** The production of the required fuel or electricity for charging. In this case, the electricity mix available in the region in which the vehicle is operated needs to be taken into account. For Germany for example, 486 g(CO_2) are emitted per kilowatt hour of produced electricity.
- **Disposal / recycling (end-of-life):** So far there has been little empirical evidence regarding the efficiency of recycling or disposal processes for BEV batteries. Experience comes primarily from hybrid vehicles, whose batteries are generally 20 to 40 times smaller than the battery of a purely battery electric vehicle and usually made from different materials. It is likely that this step of the life cycle is significantly more energy-intensive than with an ICEV, since the battery module of an electric car has a complex structure and is very difficult to break down into its individual components – and it requires a lot of energy to do so.

It is expected that, considering all life cycle stages, the technology analysis and evaluation will result in different outcomes and findings than with a single focus on the vehicle's use phase (tank-to-wheel).

[11] See https://boerse.ard.de/anlagestrategie/branchen/zweites-grossprojekt-fuer-batteriezellfertigung-in-europa100.html

[12] Cf. Federal Environment Agency (2019). However, in contrast to our model values, the CO_2 emissions caused by the construction of renewable energy plants such as solar or wind power plants are not yet taken into account.

Figure 8. LCAs provide information about real CO_2 footprints and allow system comparisons



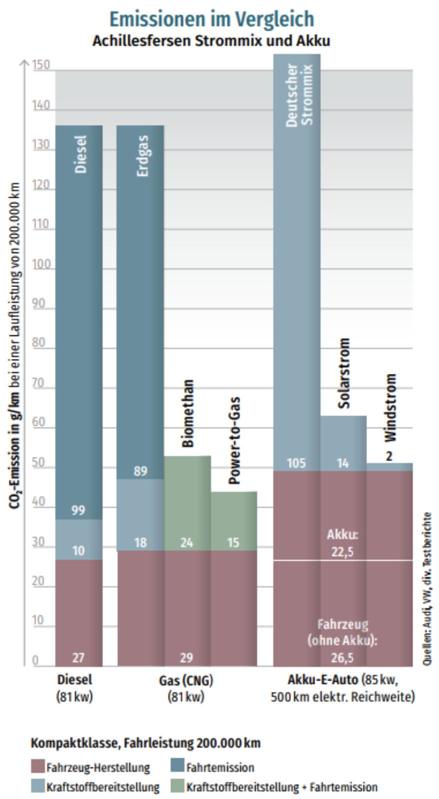
Source: Frontier Economics

Note: This is a schematic representation.

3.2 This year, the focus of public debate has already been expanded

While the regulatory frameworks and political debates currently focus heavily on supposedly emission-free BEVs, as described in Section 2.4, the public, scientific and media debate is steadilymoving towards a broader system view. Experts are therefore increasingly focusing on comprehensive analytical approaches to determine climate impacts in the field of drive technologies used in the transport sector:

Figure 9. Emissions compared



Source: *Panorama – Das Magazin des Deutschen Alpenvereins, March 2019, 71st Edition, p. 14*

- **Scientific literature** has long since used LCAs in the analysis of greenhouse gas emissions from the various drive types. Just one example of many is the publication by Ellingsen, Singh and Stromman (2016), which shows that electric drives are not more climate-friendly per se than combustion engines, but instead that the greenhouse gas footprint depends on various assumptions, including the vehicle class, the battery size and the lifetime mileage.
- The subject is also gaining attention in the **public and political debate**. Institutes such as the Ifo Institute (April 2019), Fraunhofer ISI (February 2019) and the ifeu (April 2019) take into account not just the emissions from the vehicle's use phase (tank-to-wheel), but also the greenhouse gas emissions generated when the vehicle and its fuel are being produced. The Magazin des Deutschen Alpenverein also found in an article entitled "Berg-Auto-Zukunft?" ["Mountain-Car-Future?"] that, with reference to the current German electricity mix, "when accounted for correctly, [...] battery electric cars are currently not a real win for the environment".[13]

3.3 Our study is designed to encourage higher transparency and fact-finding

The aim of our investigations is to determine the CO_2 impact today and in the future by taking into account relevant influencing factors for the BEV and ICEV drive technologies in each life cycle stage.

The analysis is based on a calculation tool that incorporates the following parameters and therefore covers all factors that are currently considered to have an influence on the LCA:

- **Vehicle class:** In this version, the compact class, the medium-sized class, the SUV class and the class of light commercial vehicles (LCV) are initially taken into account within the passenger car segment.[14]
- **Year of registration and use of the vehicle:** Starting with the year 2020, vehicle registration can be determined up to the (currently) last time of purchase in 2040. The period of use can be selected arbitrarily, with 2050 being the last year shown. Therefore the maximum period of use for a vehicle registered in 2040 is 10 years.
- **Battery capacity:** In principle, our tool automatically determines the battery capacity used for the CO_2 calculation from the choice of vehicle class. This default setting is based on the representative battery capacities currently available on the BEV

[13] Panorama – Das Magazin des Deutschen Alpenvereins, March 2019, 71st Edition, p. 12.

[14] According to the categorisation by the Federal Motor Transport Authority

market. Users also have the option, however, to make their own assumptions regarding battery size and to integrate these into the model.

- **Annual mileage:** The annual mileage can be selected at will.
- **Fuels, country of production and operation:** Thie set of parameters is completed with the choice of fuel (in this case there is also the option of modelling the blend-in of e-fuels), the choice of production and operation country and the progression of the electricity and energy mix.[15]

The tool allows to estimate the impact of varying parameters on the CO_2 impact of the considered technologies .[16] This means that assumptions used as a default can be overwritten when new information comes to light.

The study does not cover the following circumstances so far:

- The analysis focuses on estimating CO_2 emissions. Other environmental and climate-impacting aspects, such as water or raw material consumption, are not taken into account.
- The model includes gasoline and diesel ICEVs and BEVs as drive technologies. Hydrogen or natural gas ICEVs, fuel cell electric vehicles or hybrid vehicles are not included in the analysis.
- The analysis concludes at a certain level of detail. Not covered, for example, is the detailed cell structure for the various batteries available on the market (cf. Annex C).
- Individual sub-stages of the added value chain, such as CO_2 emissions from the construction of the energy infrastructure (e.g. electricity networks), charging and filling stations, etc. are not part of the analysis. The tool therefore includes what has been identified as the main drivers of CO_2 emissions along the vehicles' life cycle stages.

[15] According to scenarios from the World Energy Outlook (WEO) by the International Energy Agency (IEA).

[16] For further explanations of the calculation tool, see also **Error! Reference source not found.**.

4. A BIRD'S EYE PERSPECTIVE ALREADY REVEALS NEW FINDINGS

As described, changing from the ground-up to the bird's eye view, the focus when assessing CO_2 emissions shifts from tank-to-wheel to the LCA or cradle-to-grave approach. We have summarised the key results of our LCA analyses below. It shows that, from a broader perspective, the advantageous nature of individual technologies depends on a number of drivers and on the individual case in question, making it significantly less clear than is frequently assumed in the current debate around energy policy.

4.1 From a comprehensive perspective, CO_2 emissions are unexpectedly high in battery electric cars

As previously presented, the public debate around energy policy often perceives that battery electric vehicles do not produce any CO_2 emissions. This is not the case, however, as an LCA based on the example of a BEV – in this case a medium-sized vehicle (**Figure 9**) – illustrates. Instead, significant CO_2 emissions are produced even with BEVs:

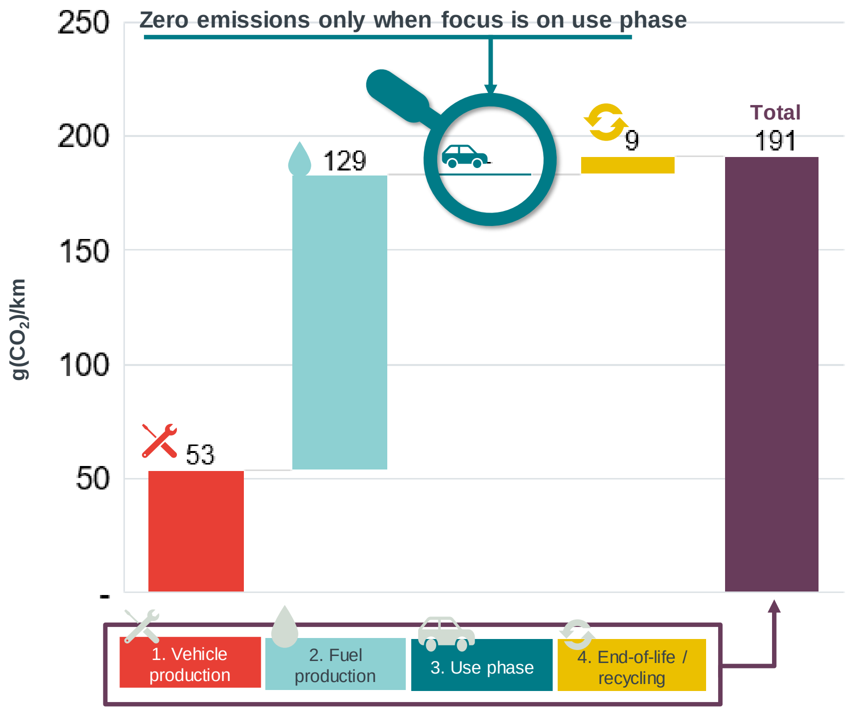
191 g (CO_2)/km

and not 0 g (CO_2)/km

is the CO_2 impact of an example medium-sized BEV today

- In the use phase, a BEV produces 0 g (CO_2)/km in CO_2 emissions.
- Over the BEV's **entire life cycle**, however, the CO_2 impact is 191 g (CO_2)/km (**Figure 10**). Of this number,
  - 53 g (CO_2)/km are generated during production of the vehicle – especially the battery (with the assumption being that the battery is made in the EU);
  - 129 g (CO_2)/km are generated during the production of drive energy (in this case the electricity for charging) in Germany: this is particularly noteworthy in that a "dynamic" development of the electricity mix is assumed. With a "dynamically" specified electricity mix, it is assumed that its CO_2 intensity will be constantly reduced according to the scenarios through the further expansion of renewable energies. This therefore means that the electricity for charging will be associated with increasingly fewer CO_2 emissions in the climate impact, year on year, and
  - 9 g (CO_2)/km are produced during recycling.

Figure 10. Overall CO_2 impact using the example of a medium-sized BEV



Source: Frontier Economics

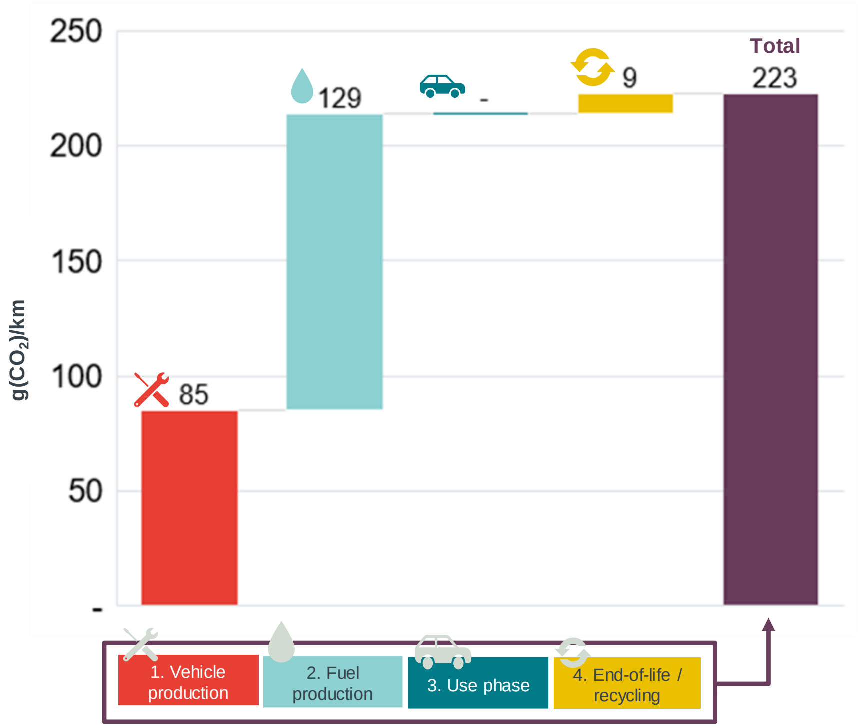
Note: Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Since this scenario assumes that the battery is produced in the EU, the comparatively climate-friendly European electricity mix is used for the required electricity demands. As already mentioned, however, around 70% of the production capacities for BEV batteries are currently based in Asia. If, for example, the Chinese electricity mix is selected for the "Vehicle production" life cycle stage, the BEV's CO_2 emissions for the entire life cycle increase in mathematical terms to 223 g (CO_2)/km (**Figure 11**).

“

A vehicle's use phase on its own has only limited informative value for the emission impact

Figure 11. Overall CO_2 impact using the example of a medium-sized BEV – Country of battery production: China



Source: *Frontier Economics*

Note: *Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, country of operation: Germany (reference scenario), country of battery production: China, dynamic*

Overall, it is apparent that focusing on the use phase (as described in Section 2.4) leads to a less meaningful CO_2 balance. Comprehensive analyses are therefore essential for technology evaluations.

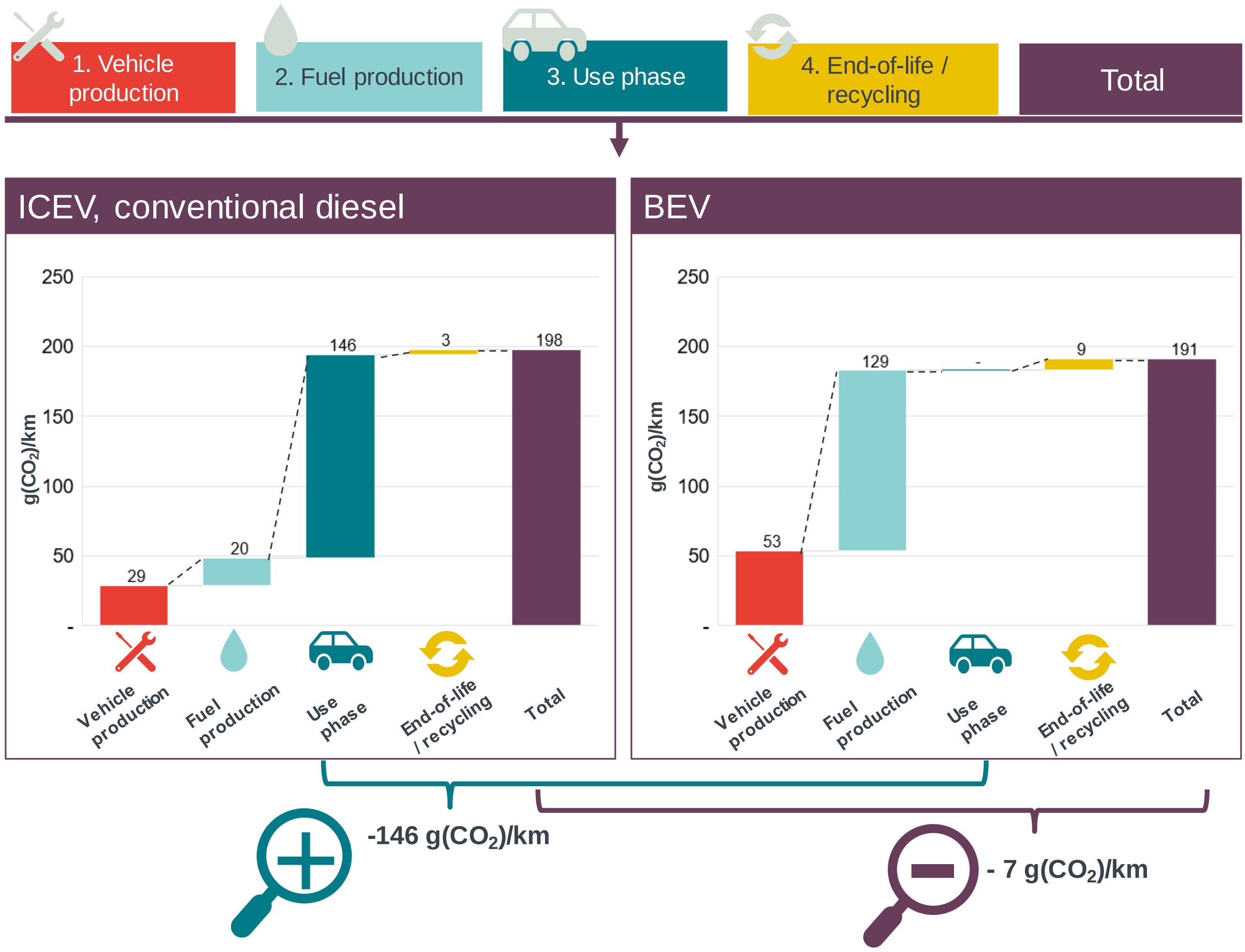
4.2 The advantage of BEV over ICEV varies significantly from case to case

In a comparison of different technologies, it can be seen under the LCA approach that the overall emissions of BEVs today and over the next few years will in many cases be on a similar level to vehicles with a combustion engine. For example, the CO_2 emissions of a medium-sized vehicle are **198** g (CO_2)/km for a diesel engine and **191** g (CO_2)/km for a BEV (Figure 12). The minimal difference in the numbers is due to the fact that

- the additional emissions of the ICEV at the vehicle production stage are significantly lower than those of the BEV, since the energy-intensive battery production stage is not applicable (+24 g (CO_2)/km).

- additional emissions from the production of diesel are also lower than from the production of electricity for charging based on the German electricity mix (+ 109 g (CO_2)/km).
- additional emissions are similar in the disposal stage.

Figure 12. Differences in CO_2 emissions between BEV and ICEV are in many cases relatively small both today and over the next few years

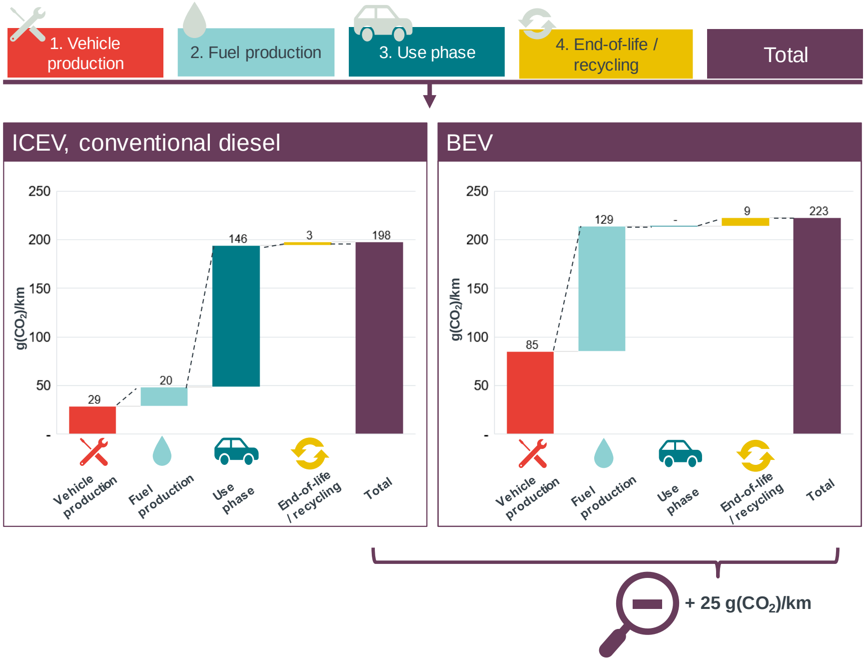


Source: *Frontier Economics*

Note: *Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*

This result can easily change through varying a variation in the assumptions. The BEV is at a disadvantage to the ICEV if the battery for the vehicle is not produced in Europe, but rather for example in China, based on the local electricity mixed used there (cf. **Figure 13**).

Figure 13. Production of the battery in China worsens the BEV's CO_2 impact



Source: *Frontier Economics*

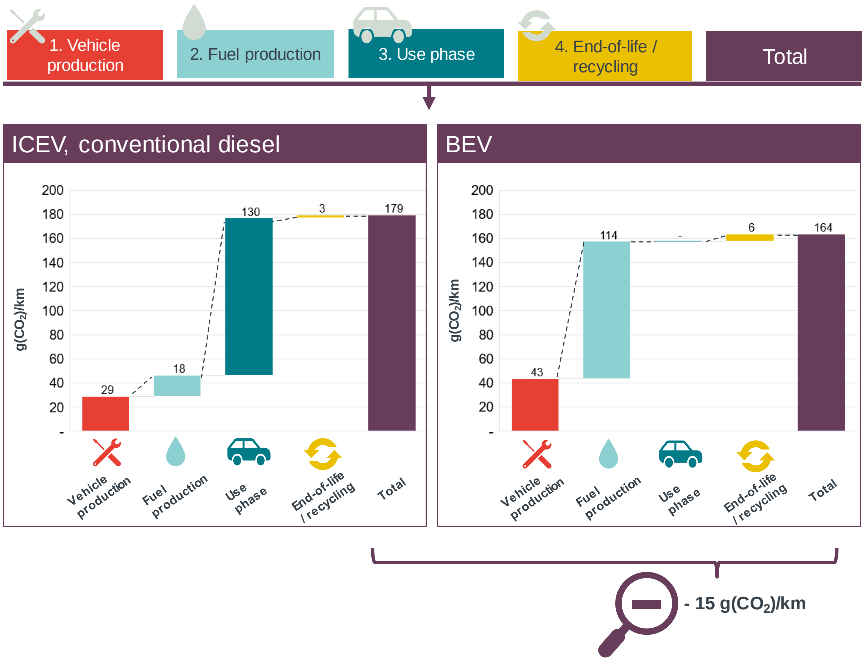
Note: *Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: China (reference scenario), dynamic*

The case studies below, in which only the vehicle class is changed, confirm this result: The advantage of the technologies in each case varies significantly depending on the case study and assumptions.

Case study – compact class

Due to the relatively low emissions generated during battery production (the assumption being that in this case a relatively small battery is installed), a compact class BEV currently has an advantage over a comparable ICEV. Based on the assumptions made, the advantage is 15 g (CO_2)/km with regard to the km-related CO_2 emissions compared to the ICEV.

Figure 14. Due to the relatively low emissions generated during battery production, a compact class BEV currently has an advantage over a comparable ICEV

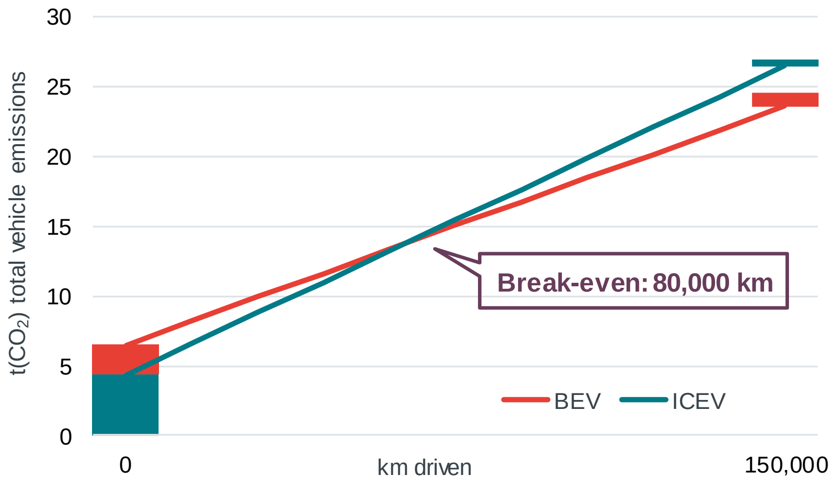


Source: Frontier Economics

Note: Vehicle type: Compact class, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Up to a total mileage of around 80,000 km, the ICEV has an advantage in terms of overall emissions. From this point onwards, with each further kilometre driven, the overall CO_2 impact improves in favour of the BEV (**Figure 14** and **Figure 15**)

Figure 15. After 80,000 km, the emissions of the compact class BEV are lower than those of the ICEV



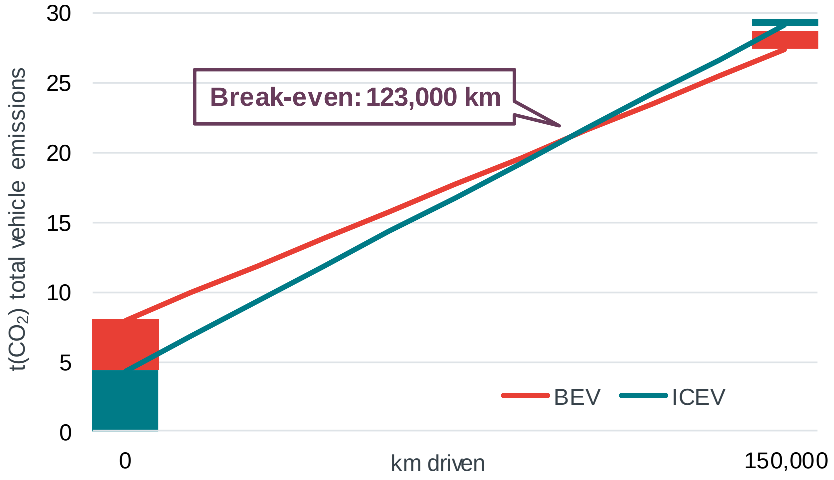
Source: Frontier Economics

Note: Vehicle type: Compact class, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Case study – medium-sized car

Other than for the compact class, the difference between the BEV and ICEV emissions in the medium-sized class is reduced in favour of the ICEV (for an analysis, cf. Section 4.2). With the selected parameter set (Figure 16), the mileage required from which the BEV fares better in terms of overall emissions increases. At around 123,000 km, this mileage is close to the end of the calculated useful life of the medium-sized vehicle in question and about 43,000 km higher than that of the compact class. This is mostly driven by the larger battery capacity and the emissions associated with its production.

Figure 16. On a medium-sized vehicle, the break-even point occurs significantly later



Source: Frontier Economics

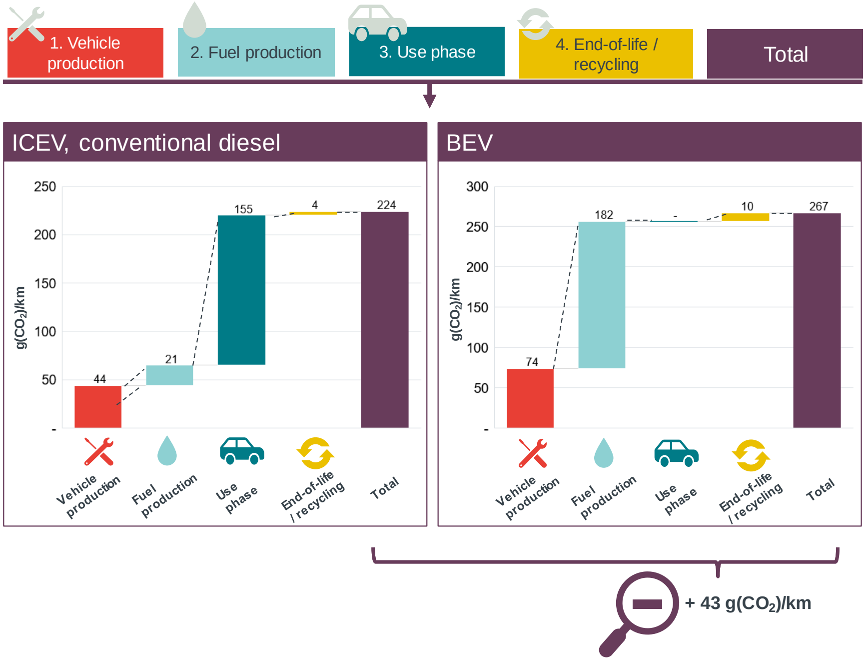
Note: Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Case study – SUV

In the SUV class, keeping all of the other parameters and assumptions unchanged, the ICEV has the advantage over the BEV: over the entire life cycle, the BEV has additional emissions of 43 g (CO_2)/km compared to the ICEV (**Figure 17** and **Figure 18**).

One reason for this is the larger battery capacity relative to the compact or medium-sized class. The BEV's production-related CO_2 burden is therefore already so large that the disadvantage can no longer be offset by lower CO_2 emissions during the vehicle's operation in the usage phase.

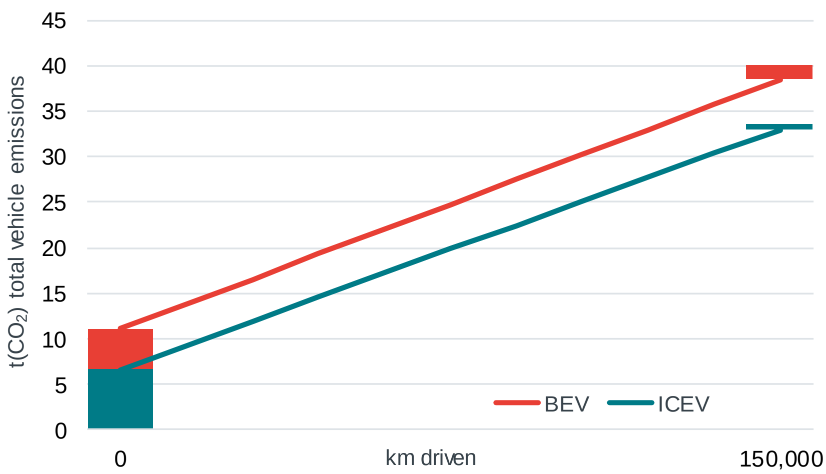
Figure 17. High production-related emissions and high consumption cause an SUV BEV to emit more CO_2 overall than a comparable ICEV



Source: Frontier Economics

Note: Vehicle type: SUV, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Figure 18. Over the entire life cycle, the ICEV has the advantage over the BEV



Source: Frontier Economics

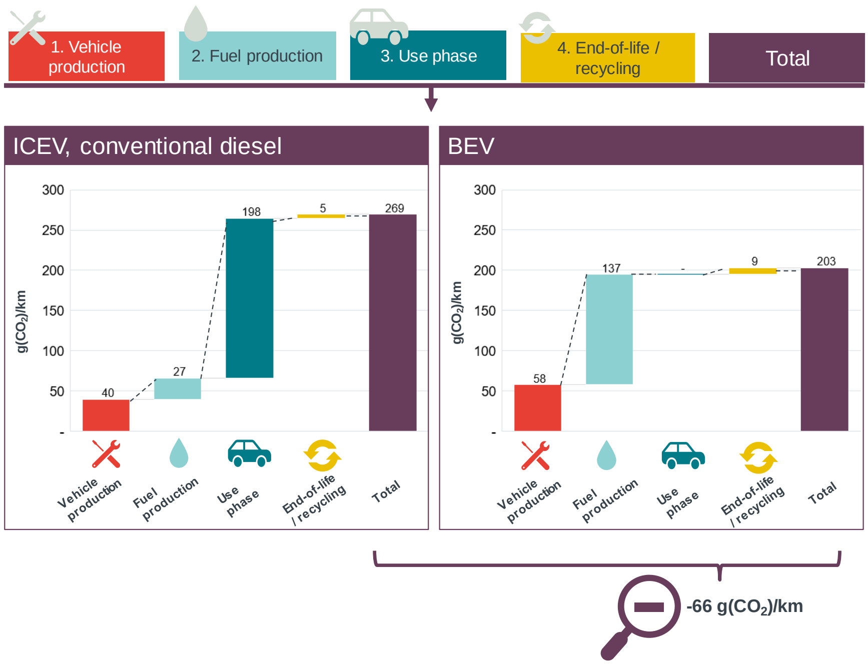
Note: Vehicle type: SUV, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Case study – Light commercial vehicle

Light commercial vehicles are used for a range of purposes. For example as customer service vehicles for craft enterprises in urban areas (possibly on shorter day trips) or in more powerful variants with, for example, higher payload potential, for longer distances. This variety of applications for LCVs is also evident in the battery electric LCVs advertised by manufacturers nowadays.

Hence, it would have been possible to use various battery capacities for these investigations. As expected, the example of an LCV with a comparatively small battery capacity, again with all other parameters remaining the same, shows an advantage for the battery electric variant, whose CO_2 emissions are 203 g (CO_2)/km, compared to 269 g (CO_2)/km for the comparable ICEV (**Figure 19**). In this example, the "CO_2 burden" from battery production is comparatively small (**Figure 20**). The break-even point in favour of the BEV in this case stands at a mileage of only around 38,000 km.

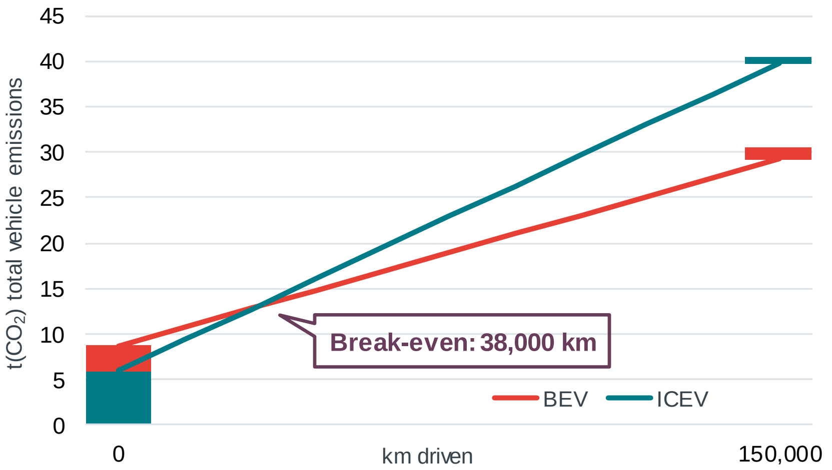
Figure 19. Due to the relatively high energy demand, the BEV currently has the advantage in the smaller LCV performance range



Source: Frontier Economics

Note: Vehicle type: Light commercial vehicle (37 kWh battery), year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic

Figure 20. For LCVs with a small battery capacity, the break-even point is achieved early on in the life cycle

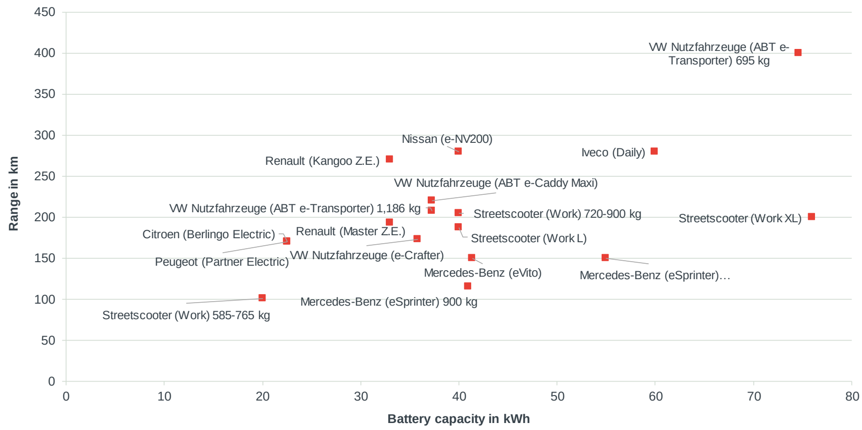


Source: *Frontier Economics*

Note: *Vehicle type: Light commercial vehicle (37 kWh battery), year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*

The LCV class must cover a much wider spectrum of use compared to a passenger class car. Longer ranges and a high vehicle load potential in particular mean that more powerful vehicles are needed. The extent to which BEVs with adequately larger battery capacities and therefore also a higher tare weight make sense in this segment (LCVs are limited to a max. total weight of 3.5 t) is questionable. For technical reasons, liquid fuels with their high energy density therefore have an advantage for customer requirements at high vehicle load weights (**Figure 21**).

Figure 21. Light commercial vehicles are available with various battery sizes



Source: *eurotransport.de (https://www.eurotransport.de/artikel/grosse-marktuebersicht-elektro-transporter-16-transporter-modelle-mit-e-antrieb-10490177.html, retrieved on 26.08.2019)*

However, from a climate impact perspective, BEVs and ICEVs are again comparable in higher LCV performance ranges. If a more powerful vehicle, e.g. with a 75 kWh battery (cf. the current model summary in **Figure 23**), is taken into consideration, the CO_2 emissions of the BEV, at just under 270 g (CO_2)/km, are at approximately the same level as those of the ICEV. The break-even point in this case is only reached after 125,000 kilometres. In the same way as for the SUV case study, the larger battery also leads to higher production emissions in this example, which virtually cancel out the BEV's advantage in the usage phase.[17]

Summary: General statements regarding the advantageous nature of individual drive technologies are not possible – BEV and ICEV currently each have their own advantages

Overall, the case studies show that, for the various vehicle classes considered with otherwise identical assumptions regarding the influencing parameters, the overall CO_2 impacts for BEV and ICEV are in some cases at a similar level, but in some cases also exhibit significant differences – with emissions-related advantages and disadvantages on both sides.

4.3 Many influencing factors determine the overall CO_2 impact of the drive technologies in individual cases

A whole series of parameters affect the overall CO_2 impact

The selected case studies show that a series of parameters have an impact on the overall CO_2 emissions of ICEV and BEV with varying sensitivities. The key influencing factors in this are:

- **Vehicle size / vehicle segment:** The larger and heavier a vehicle or its payload is to be, the more electricity or drive energy are required to move it. The dimensions of the battery capacity and consumption of final energy are also geared towards this.
- **Range:** The further the range a vehicle is able to travel before needing to be refuelled or recharged, the larger the battery required. While in a compact vehicle a tank filled with liquid fuel, such as diesel, has enough energy to drive the car for more than 800 km without being refuelled, this distance is currently virtually impossible to achieve with a BEV. Generally, BEV manufacturers need to consider in more detail how much battery capacity is required. On the one hand, more capacity is desirable since it gives the vehicle a larger range or allows more weight to be hauled. On the other hand, however, the amount of energy needed to produce one kilowatt hour of battery capacity is high and rises with every further kWh of capacity.

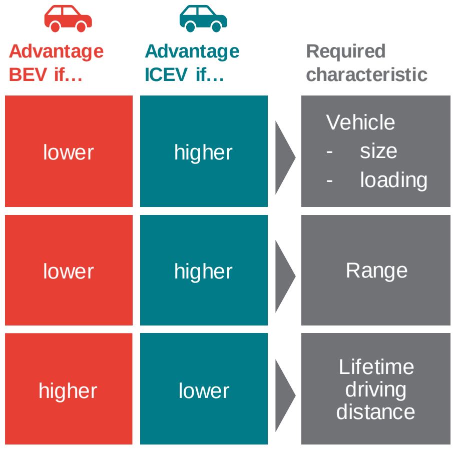
[17] The BEV's usage phase advantage is reduced in this case not only by the higher production emissions, but also by the higher consumption of light commercial vehicles, which at the same time carry a heavier load due to the larger battery.

- Batteries with a higher capacity are also significantly larger and most importantly heavier, which results in spatial limitations to the battery capacity. In a typical BEV compact class car, space, weight and cost reasons therefore imply that batteries with a 40 kWh capacity are most commonly used, and these allow a range of around 200 km. The production of a 40 kWh battery causes significantly lower CO_2 emissions than the production of a larger battery with a charge capacity of for example 100 kWh (installed in the Tesla Model S, for instance).

- **Lifetime mileage:** If a vehicle does not use 100% renewable energy, CO_2 emissions are produced directly or indirectly with every kilometre driven.
- **Country of operation:** The CO_2 intensity of each kilowatt hour of produced electricity depends on the electricity mix of the country in which the vehicle is operated. For Germany, for example, a CO_2 intensity (including emissions from system expansion) of around 467 g (CO_2)/kWh exclusive of and 516 g (CO_2)/kWh inclusive of renewable energy systems construction is expected in 2020.
- **Country of production:** For the energy-intensive production of the battery in particular, it matters which electricity mix the manufacturing country has. The electricity mix in China, the country of origin for the majority of batteries currently installed in vehicles, has a significantly higher CO_2 intensity (743 g (CO_2)/kWh in 2017) than that of Japan (581 g (CO_2)/kWh in 2017), followed by the USA (480 g (CO_2)/kWh in 2017) and the EU (378 g (CO_2)/kWh in 2017).
- **Period of use:** The period of use is relevant if changes over time, e.g. with regard to the vehicle use of new cars, or an increase in the renewable proportion of the electricity or energy mix, are taken into account. In our calculations for the BEV, for example, we assume that the electricity mix for the electricity for charging will become "greener" over the lifetime of the vehicle ("dynamic" perspective; NB: in the case of fossil fuels, we are not yet assuming an energy mix that becomes greener e.g. through the increased use of bio-fuels or the blend-in of green, synthetic fuels). Different overall emissions are produced, for example, if a static electricity mix is used for the vehicle's lifespan. This would be the case if we were to assume that the proportion of renewable energies in electricity generation in the country of operation (in this case: Germany) were to remain stable and at the present level through the vehicle's period of use. This sensitivity can be selected in the calculation tool.

The advantages of the individual technologies with regard to the applications (**Figure 22**) and their overall CO_2 impact result from the emissions during the individual life cycle stages:

Figure 22. Trends of ICEV and BEV advantages in applications with selected comparative categories



Source: Frontier Economics

- **Commissioning:** The BEV starts out with a larger "CO_2 burden" than the ICEV since the production of its batteries in particular both today and in the foreseeable future, generates significant CO_2 emissions regardless of where the batteries are produced.
- **During the vehicle's operation:** The production of the electricity for charging for BEV operation is currently – and for the foreseeable future – associated almost all over the world with CO_2 emissions. In many cases, the emissions from generating electricity for charging are lower in the overall emission impact than the emissions produced from the use of purely fossil fuels in an ICEV. In these cases, the BEV can therefore compensate for the higher manufacturing emissions during the use phase compared to the ICEV when driven to a high mileage, allowing it to reach a break-even point. However even in the event of lower CO_2 emissions per kilometre driven, there does not necessarily have to be a break-even point: as soon as the battery in the BEV has to be replaced, new emissions are created through the battery's production which then need to be compensated for through even more driving.
- **Disposal / recycling:** The amount of work required to dispose batteries depends on the size of the battery. Even when disposing of a BEV with a 40 kWh battery, more emissions are produced than with a comparable ICEV; however from a present-day perspective these are at a lower level compared to other segments of the life cycle.

One criterion that cannot be ignored from a consumer's perspective these days is the vehicle's range. A computational comparative analysis for the compact class is therefore also carried out in the following excursus, in which a battery is hypothetically dimensioned in such a way that an identical range can be achieved for vehicles of both drive types.

EXCURSUS: COMPARISON OF VEHICLES WITH AN IDENTICAL RANGE

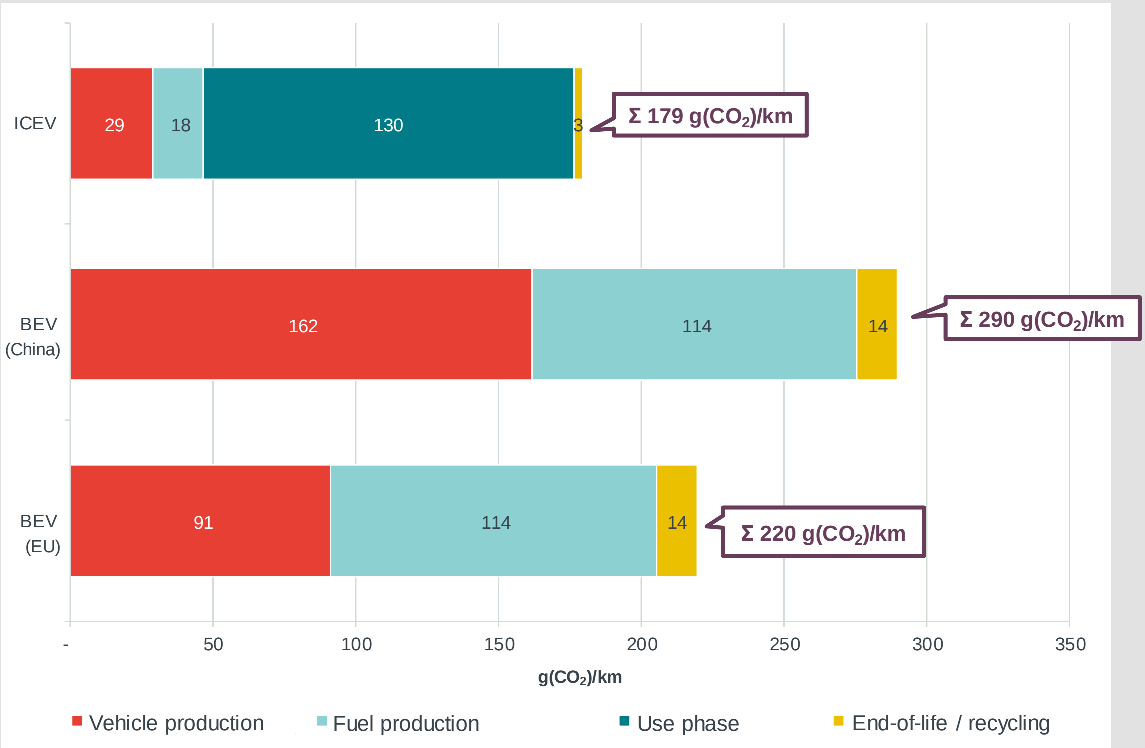
One of the biggest limitations of battery electric vehicles currently is their range. With compact class vehicles such as the VW Golf with a conventional combustion engine, distances of 800 km can be covered without a problem on one tank, based on a tank size of 40 l and a consumption of 5 l/100 km.

These ranges are not reached by the battery electric vehicles currently available. A Nissan Leaf, for example, which is also a compact class vehicle, with a battery capacity of 40 kWh and a consumption of 21 kWh/100 km, cannot cover even a quarter of this distance.

If the battery capacity (ignoring technical limitations) were to be scaled up to meet the required range, a battery with a capacity of around 170 kWh would be needed in the VW Golf example for a range of 800 km. Unlike in the other calculations, we simply assume the complete charging and discharging of the battery.

In addition to a range of practical limitations, this would also have a negative impact in terms of CO_2 emissions. With the current electricity mix, the production of this type of battery in China alone would cause almost as much CO_2 as a comparable vehicle with a combustion engine over its entire lifetime (**Figure 23**). Even when produced using supposedly "green" methods in the EU, the life cycle emissions are more than 35% higher than those of the ICEV.

Figure 23. With the same range, almost as many emissions would be caused by the production of a battery for a compact BEV as over the entire lifetime of an ICEV



Source: *Frontier Economics*

Note: *Vehicle type: Compact class, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), alternatively China, dynamic*

5. IN FUTURE, WITH ICEV AND BEV, THERE WILL BE AT LEAST TWO TECHNOLOGY OPTIONS FOR SUSTAINABLY REDUCING CO_2

So far, we have largely focused on the vehicles' CO_2 emissions today and in the near future. In the previous section, for example, we based all ICEV analyses on fossil, conventional fuels as they are used today.

For evaluating the fitness for the future of the various drive technologies, in addition to the current climate impact, however, the future potential for further CO_2 avoidance is also an important aspect. Below, we will address the ICEV's and BEV's various CO_2 avoidance potential options and illustarte the spectrum of future technological solutions.

5.1 In the future, ICEV CO_2 reductions are possible through the blend-in of e-fuels

In addition to the previous analyses focusing on the vehicles' current climate impacts, in the following we will work out what potential both BEV and ICEV have in future for helping to achieve the climate goals. Not only does the increasingly renewable energy-based production of the vehicles play a decisive role here, but so too does the provision of renewable energy-based drive energy:

BEVs will be able to reduce their CO_2 footprint in future if electricity from renewable energies is used for battery production and the CO_2 intensity of the electricity for charging is reduced.

However, in the future the CO_2 footprint of ICEVs can also be reduced significantly by using increasing amounts of synthetic fuels sourced from renewable energies (known as e-fuels), instead of the conventional fuels assumed in Section 4 (with a small amount of bio-fuel added). From production to use, e-fuels generated from renewable energies achieve overall GHG neutrality: although CO_2 is emitted during the usage phase, exactly as with conventional fuels, the CO_2 is taken from the environment during the production of the e-fuel. The climate impact is therefore equilibrated.

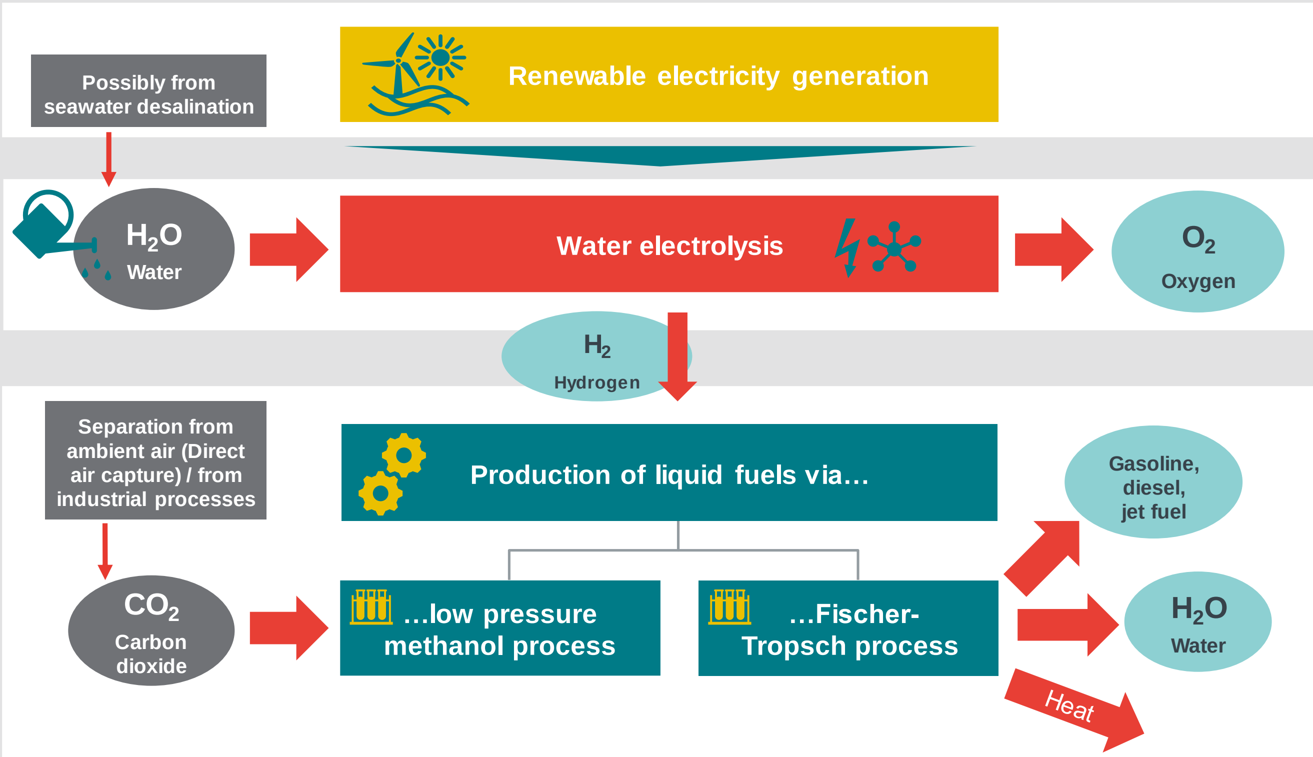
EXCURSUS: PRODUCTION OF E-FUELS FROM RENEWABLE ENERGIES

The production of e-fuels (**Figure 24**) is based on electricity generated from renewable energies and two conversion steps:

- electricity is first generated from renewable energies;
- via electrolysis, using electricity, water is converted into hydrogen (and oxygen) (in dry regions, the water required can be obtained from sea water desalination plants); and
- in a further step, synthetic fuel is produced via methanol or Fischer-Tropsch synthesis from the hydrogen and the use of carbon (CO_2).

To achieve climate neutrality, the required CO_2 must come from a self-contained circuit. This means that the CO_2 must be taken from the air, biomass or from emission sources that are available anyway (e.g. in concentrated form from existing industrial processes).

Figure 24. Production of e-fuels



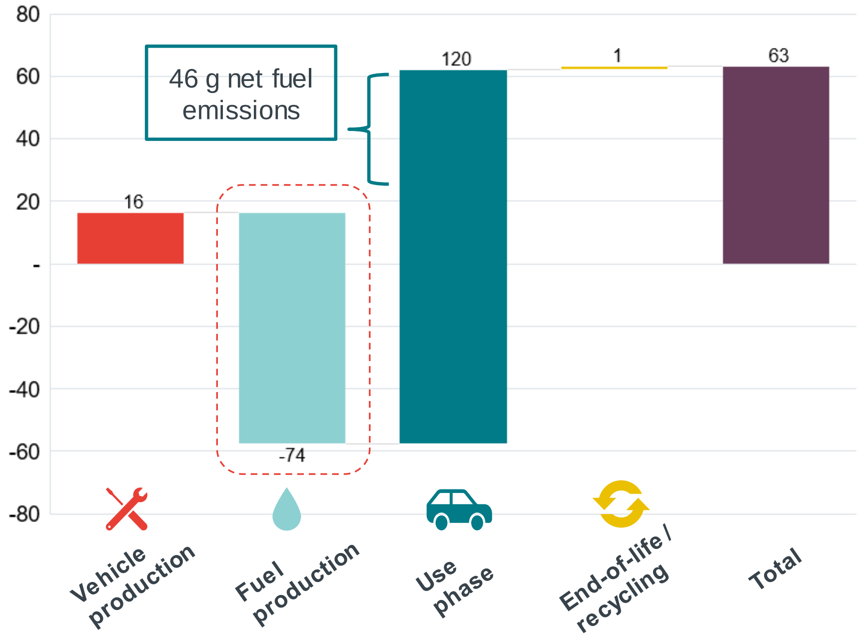
Source: Frontier Economics

In the case study below (**Figure 25**) a mixture of fossil and synthetic fuels is used throughout the vehicle's period of use (assumption here: 2040 - 2050). Specifically, we consider a 70%[18] blend-in of e-diesel to fossil diesel. The results show the following picture:

[18] For the admixing ratio of 70% in 2040, we rely on the mean value of the e-fuel ramp-up curves (p. 33) from the study by Prognos AG, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT and the German Biomass Research Centre DBFZ (2018) "Status and Perspectives of Liquid Energy Sources in the Energy Revolution"

- The emissions during the vehicle's usage (tank-to-wheel) are +120 g (CO_2)/km for the ICEV.
- The CO_2 emitted during use is captured previously during the production of the e-fuel (well-to-tank), e.g. from the environment or a biogenic source. This yields the negative emissions shown in **Figure 25** (below also the CO_2 credit) of -74 g (CO_2)/km.
- Thus, in this example with a 70% blend-in of e-fuels for the drive energy, emissions of 46 g (CO_2)/km remain aggregated over the production and use (i.e. well-to-wheel).
- The overall CO_2 impact according to the LCA for this ICEV is therefore around 63 g (CO_2)/km.

Figure 25. Through the blend-in of e-fuels, a CO_2 credit occurs in the generation of the drive energy



Source: *Frontier Economics*

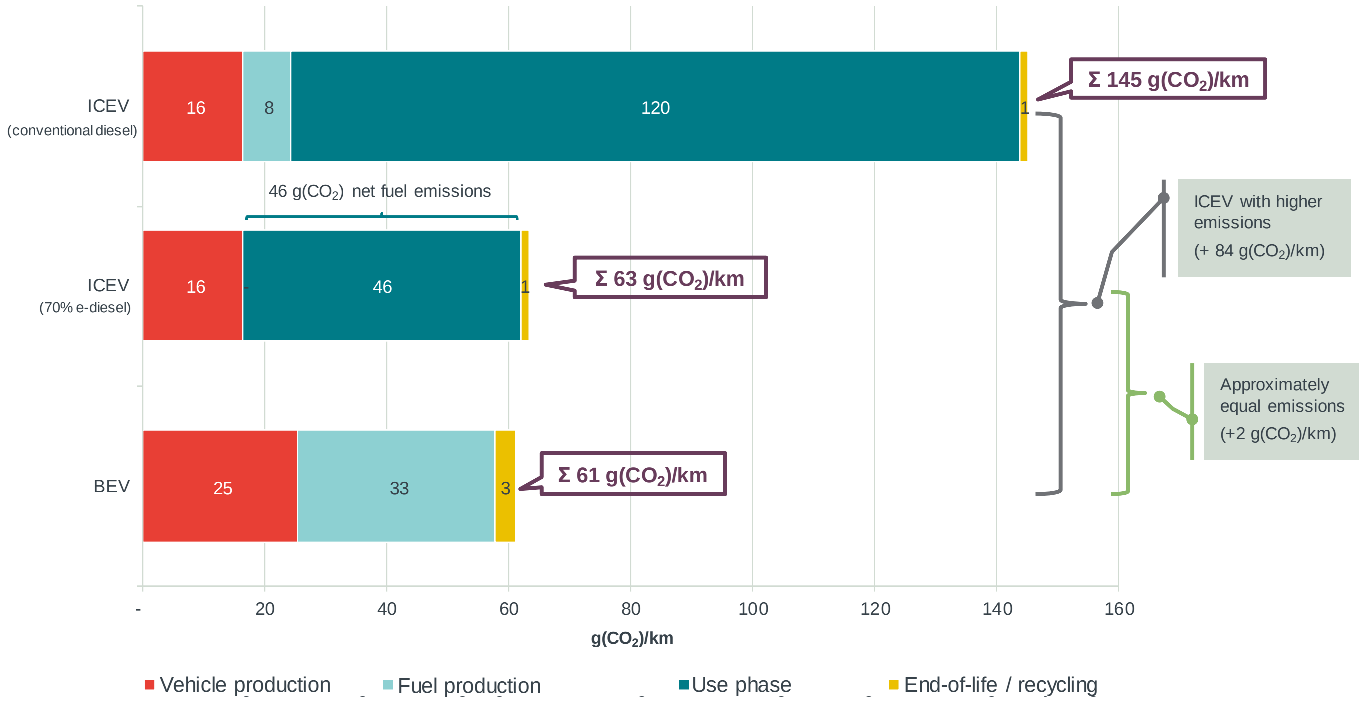
Note: *Vehicle type: Medium-sized car, year of purchase: 2040, period of use: 10 years, annual mileage: 15,000 km, fuel: Fuel mix (share of e-diesel: 70%), country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*

5.2 By blending in e-fuels, also in the future the overall CO_2 impact of the ICEV and BEV will remain at the same level

The comparison below shows by way of example that ICEV and BEV – with the fundamental assumptions around the increase in renewable electricity for charging in the country of operation (here: Germany) and the blend-in of e-fuels (in this case 70%) – can in future be on a similar level in terms of the per km-related overall CO_2 impact (**Figure 26**). It appears that

- the overall emissions of the ICEV through the blend-in of 70% e-fuels are reduced to 63 g (CO_2)/km (in comparison to this, an ICEV running on 100% conventional diesel would be around 145 g (CO_2)/km);
- the BEV's CO_2 emissions, for which the electricity for charging has an average renewable energy share of 82% from 2040 to 2050, are around 61 g (CO_2)/km; and
- therefore an ICEV will generate around the same volume of CO_2 emissions as a BEV through blending in e-fuels in this scenario.

Figure 26. Potential for CO_2 reduction through the increasing use of renewable electricity for charging in the BEV and by blending in e-fuels in the ICEV

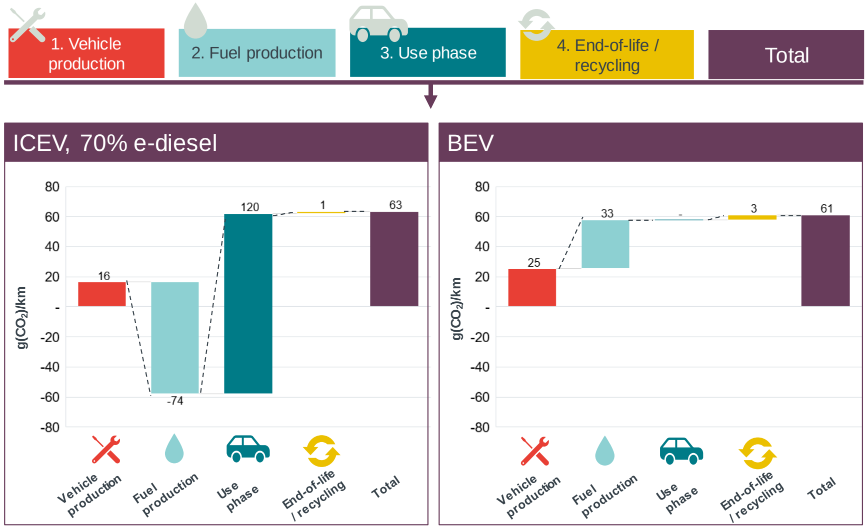


Source: *Frontier Economics*

Note: *Vehicle type: Medium-sized car, year of purchase: 2040, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel with 70% e-diesel added; country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*

The reason for this finding is the "CO_2 credit" for the climate-neutral production of synthetic fuel from renewable energies (**Figure 27**).

Figure 27. As a result of the CO_2 credit from the production of fuel, the overall emissions of ICEV and BEV are on a similar level



Source: *Frontier Economics*

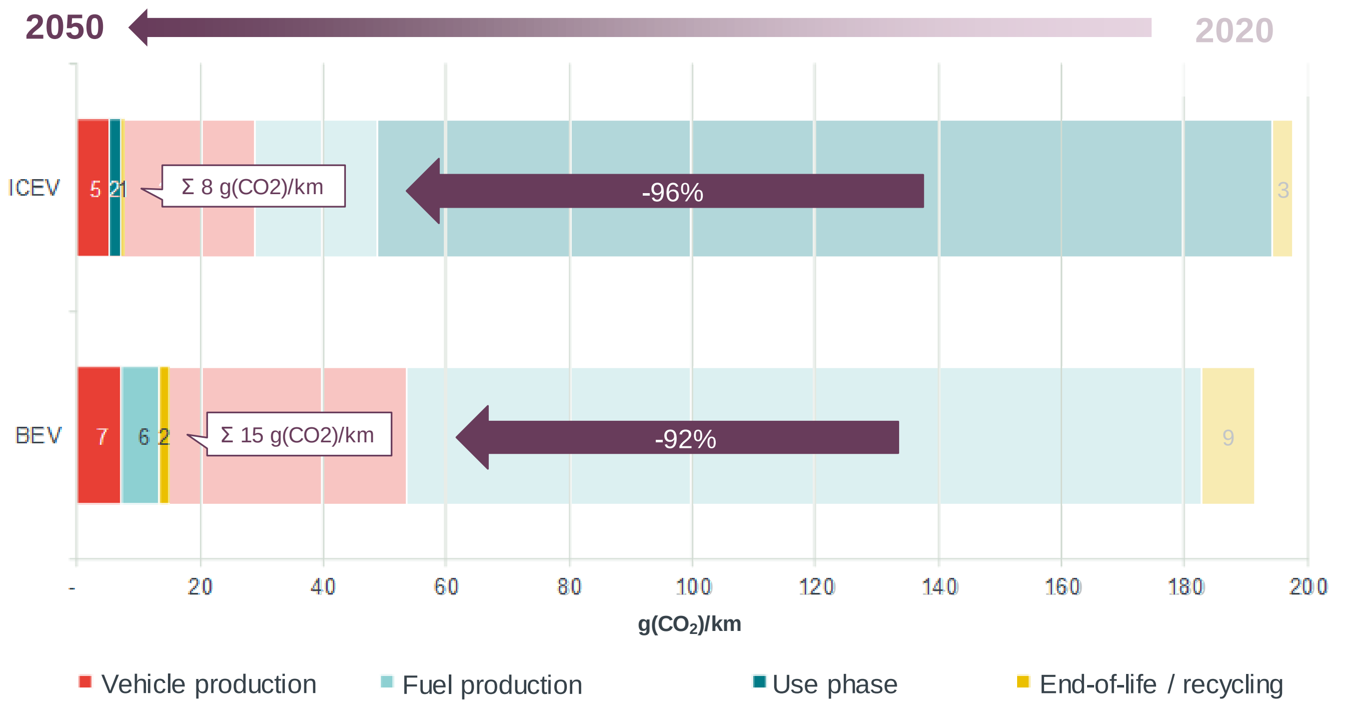
Note: *Vehicle type: Medium-sized car, year of purchase: 2040, period of use: 10 years, annual mileage: 15,000 km, fuel: diesel with 70% e-diesel added; country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*

5.3 As renewable energy shares increase, targeted technology options will be available with ICEV and BEV

> For GHG neutrality, there are multiple targeted technologies available with ICEV and BEV

Until 2050 and thereafter, both of the technology options indicated offer the potential required to deliver the CO_2 emissions savings through to GHG neutrality. The scenario shown in **Figure 28** shows the CO_2 emissions of vehicles with an electricity mix featuring almost 100% renewable energies and an e-fuel blend-in of 100%. Compared to 2020, emissions for ICEV and BEV fall by 96% and 92% respectively. This would mean that the overall impact of CO_2 emissions would be between just 8 and 15 g (CO_2)/km, depending on the technology. These low residual emissions will disappear completely in the even more distant future, even if there are no more emissions for renewable energy plant construction and complete recycling and the complete avoidance of all material-related emissions are possible.

Figure 28. Around 2050, all of the drive technologies considered could achieve virtual climate neutrality



Source: *Frontier Economics*

Note: *The scenario shown in the background corresponds to the scenario outlined in Section 4.2: Vehicle type: Medium-sized car, year of purchase: 2020, period of use: 10 years, annual mileage: 15,000 km, lifetime mileage 150,000 km, fuel: diesel, country of operation: Germany (reference scenario), country of battery production: EU (reference scenario), dynamic*
The scenario shown in the foreground is based on the following different parameters: for the year of purchase, we have chosen 2049 – the last year that can be displayed in the calculation tool – while the lifetime mileage remains at 150,000, as in the original scenario. However this time it is covered entirely with the starting parameters for 2050. Fuel: fuel mix (100% e-diesel), country of operation: still Germany (albeit using the optimistic scenario), country of battery production: still the EU (albeit using the optimistic scenario).

> Technology mix in the transport sector is a justified and necessary requirement for achieving climate goals

The case studies listed show that, in terms of future climate neutrality, not one, but rather several drive technology options are available. This diversity also offers the potential to meet the various mobility requirements in the future without compromising climate protection targets or practical reliability, such as:

- **BEV technology**, on the basis of a growing share of renewably produced electricity, offers an advantage for lighter passenger cars on shorter distances in regions with an easily expandable charging infrastructure (e.g. also for light commercial vehicles used over short distances).
- **ICEV technology**, with the increasing use of e-fuels, is generally suitable for passenger cars with higher performance requirements (such as upwards from the medium-sized vehicles and SUVs).

Synthetic fuels are also an option as a medium-term measure since they can be used in the current stock of vehicles without technical modifications. The handling and use of e-fuels are relatively simple. From a present-day perspective, their use will be almost indispensable in certain applications and for modes of transport that go beyond the classes of vehicle examined in this study (such as aviation).

6. FROM A REGULATORY AND CLIMATE POLICY PERSPECTIVE, A MOVE TOWARDS TECHNOLOGICAL OPEN-MINDEDNESS IS REQUIRED

The climate impact of drive technologies examined in this study in the field of passenger cars and LCVs have shown that a mix of technologies should be preferred over a restricted technology set. To reduce CO_2 emissions sustainably, it is sensible and recommended to design the regulatory framework for the transport sector in a way that not only battery electric drives but also drives based on e-fuels (ICEV) are promoted on an equal footing. Based on this, more specific recommendations for action for policy-makers will be outlined at the end of this section.

6.1 E-fuels must be promoted on an equal footing alongside electromobility for climate policy reasons

The EU CO_2 fleet directive for passenger cars and LCVs

is to be opened for target-compliant technologies

In today's political status quo, regulatory frameworks are in effect that are restricted solely to the use of vehicles in the context of reducing CO_2 emissions in road transport. From this perspective, BEVs have an advantage since renewable fuels, which are used as e-fuels in ICEVs, are not credited in any form. There is no consideration of e-fuels, for example, in the EU CO_2 fleet directive for passenger cars and LCVs.

As the previous analysis has shown, e-fuels present an important potential technological solution for achieving ambitious climate goals. For the various vehicle classes and technologies, the following results can be observed in relation to CO_2 emissions over the entire life cycle:

- Taking into account the current and expected short-term situation in the electricity and energy markets (up to about 2030), ICEVs (with today's conventional fuels) and BEVs (with the current and expected renewables expansion in the electricity mix up to 2030) are on a similar level overall in terms of CO_2 emissions.
- This result may vary, however, depending on the individual case. For example, ICEVs tend to be more advantageous for cars with higher performance levels (e.g. from medium-sized passenger

cars onwards), while BEVs have lower emissions on vehicles with lower performance (compact to medium-sized, depending on parameter set).

- Significant factors on the overall CO_2 footprint of the BEV are, for example, the location of the battery production and the progression of the share of renewables within the electricity mix available in the country of operation.
- Both technologies are available as a potential solution for achieving the climate goals towards GHG neutrality: ICEVs with a growing use of e-fuels and BEVs with an increased use of renewably produced electricity, used both for charging the vehicle and for producing the batteries.

To harness the potential of these technologies for de-fossilising road transport, they must be recognised as equals in policy circles and in regulatory frameworks. A targets-compliant technology mix is an important requirement for the successful transformation process towards a GHG-neutral transport sector.

6.2 Costs and customer needs also favour an equal-status technology mix

The CO_2 LCA has shown that multiple technologies are able to achieve de-fossilisation of road transport in the long term. Further important facts also justify opening up and adapting the relevant regulations:

Consumers

should be able to choose CO_2-saving technologies themselves

in order to be able to accommodate their very diverse mobility needs

Technology mix safeguards diverse needs in road mobility

Individual mobility has a high economic value: This is why it is important, especially in the passenger car sector, to also accommodate the multiple demands on mobility in the future. Various vehicle segments and driving profiles (rural or urban driving, short or long distances, etc.) will need to continue to be covered. Being able to access a broad mix of technologies will therefore offer the opportunity to reduce CO_2 emissions and at the same time accommodate the individual needs of various users. This means that customers who want to retain their mobility habits and continue using vehicles with liquid fuels (fast fuelling, long ranges) will be able to make a contribution to climate protection by using increasingly green fuels.

LCVs could also benefit from the diversity of technologies since they, like passenger cars, serve a broad spectrum of use options. These use options are associated with a number of different requirements: In the case of "small" LCVs, which are primarily used to cover short distances, BEVs with (relatively) small batteries have an advantage. For larger LCVs, which would need larger batteries to cover longer distances, the size and weight of the battery would cause a significant restriction in the potential payload, which means that the use of e-fuels may be beneficial.

Technology mix relieves pressure on the expansion of renewable electricity generation and transmission grids in Germany

The earlier analyses have shown that the use of BEVs is favourable when the energy used both to produce the battery and to charge the vehicle has a low emissions intensity.

In terms of electricity especially, Germany is still facing a major challenge – an energy supply based exclusively on domestically produced renewable energy appears somewhat unrealistic. There are significant obstacles here in terms of site availability and also acceptance issues around expanding locations for production facilities (especially for onshore wind).

A technology mix

allows the energy revolution to be more robust with lower economic costs than a "one-size-fits-all" strategy

Thus, in future renewable energy will need to be imported into Germany. Chemical energy sources such as e-fuels offer a high energy density, which has significant benefits in terms of transport and storage. For synthetic fuels and combustibles, the existing infrastructure such as pipelines, the network of filling stations and storage facilities can already be used to a large extent. This also reduces the need to expand electricity grids in Germany. An issue that also lacks support or even acceptance in some parts of the population.

The use of e-fuels to defossilise the transport sector would therefore also bring relief to some problems in the context of expanding the future (renewable) energy supply in Germany.

Technology mix strengthens a robust supply structure

In order to guarantee unlimited mobility in the future too, a comprehensive geographical coverage with the relevant final energy (obtained from renewable energy sources) is essential.

An abrupt changeover to exclusively battery electric vehicles would require a rapid expansion of the charging infrastructure and would likely lead to gaps in the supply of mobility.

For e-fuels, existing infrastructures can be used immediately without expansion causing additional emissions or costs. In Germany alone, there are currently 14,100 filling stations[19] that ensure a nationwide supply network.

The promotion and introduction of e-fuels using the existing infrastructure for liquid fuels can therefore safeguard the supply of mobility while the infrastructure required for the use of BEVs is being expanded.

[19] https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/deutschland/tankstellen-in-deutschland/, retrieved on 10.09.2019

The technology mix can also ensure that the expansion of the charging infrastructure is only pushed ahead where it makes economic and ecological sense to do so.

USE OF EXISTING INFRASTRUCTURE CAN TAKE THE PRESSURE OFF THE EXPANSION OF THE CHARGING INFRASTRUCTURE

To allow the comprehensive use of electromobility, the universal roll-out of a charging infrastructure is needed. It is not so much the actual charging infrastructure that is a significant cost driver, but the system-wide provision of the required capacities – both with regard to the networks and the availability of generating capacity.

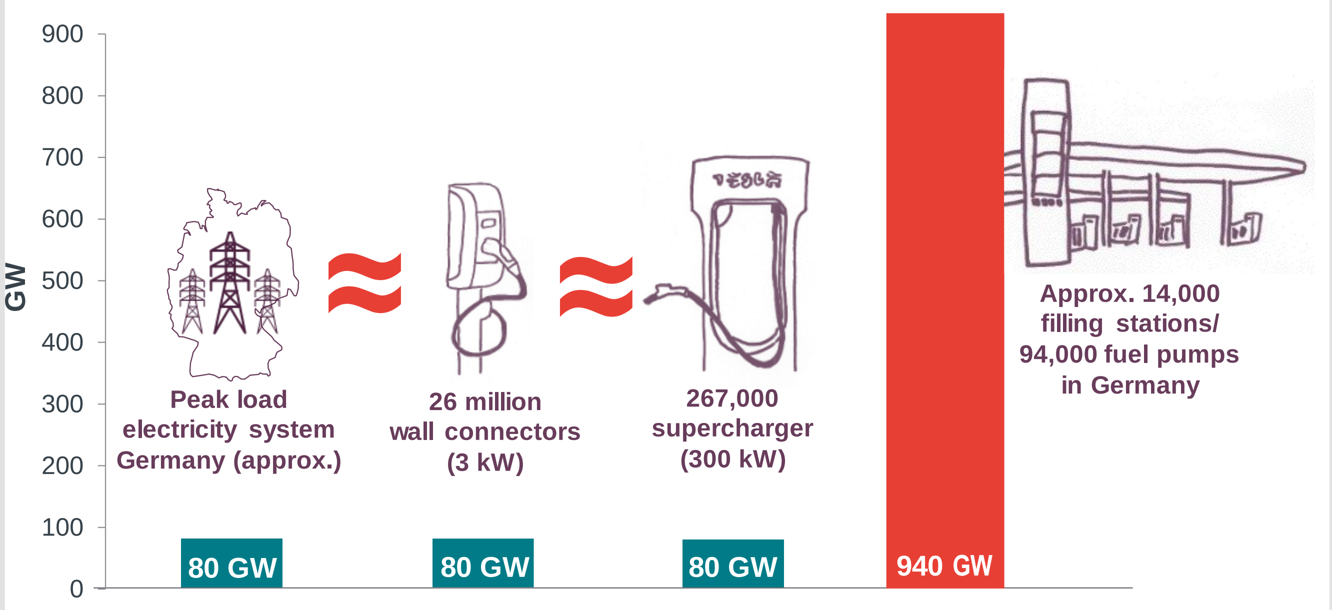
It should also be taken into account that the charging and refuelling infrastructure needs to offer options: It is the core characteristic of mobility that the exact traffic streams can only be partially predicted in terms of where and when they will happen. This is all the more true for Germany, with its location in Central Europe, and the resulting transitory traffic. It is therefore essential to not scale up the refuelling and charging infrastructure to allow optimised utilisation, but to accommodate regional peaks. As a result of these, large parts of the infrastructure will, by default, only be used for short periods of time and there will be a significant under-utilisation on average.

A simple rough calculation illustrating the (high) level of the current supply infrastructure for vehicles and the extent to which the electricity charging infrastructure would have to be expanded to match this can be seen in **Figure 29**:

- In Germany, around 94,000 fuel pumps are available at filling stations. If the average duration of the refuelling process, the flow rates and the energy density are taken into account, the average "output" with which energy is transferred to the vehicle during a refuelling process is around 10 MW, i.e. 10,000 kW. In other words, with the existing filling station infrastructure, Germany has the installed equivalent of a (secured) total capacity of **940 GW**.
- By way of comparison, the electrical charging output of a conventional "wall box" is only around 2 to 3 kW, and even "super-chargers" only achieve around 300 kW. The current peak load on the electricity grid (for all electricity consumers in Germany) is currently only around **80 GW**.

These orders of magnitude make it clear that, even if the greater efficiency of electromobility is considered, the nationwide use of electromobility will lead to a multiplication of the power to be provided in the electricity system even if the country were to aim to achieve a level of supply that is currently established at filling stations.

Figure 29. Output potential of the current filling station network compared to the provision of electricity in the mobility sector



Source: Frontier Economics

Note: 940 GW thermal; estimated total installed output of the current filling station infrastructure. 80 GW electrical; current peak load on the power grid (for all electricity consumers in Germany).
The orders of magnitude are seen to be relatively constant over time, with marginal changes in recent years.

With an technology mix, climate protection can even take place with the current vehicle stock

ICEVs currently represent majority of the vehicle stock of the global fleet – 96% of the total of around 1.3 billion vehicles are combustion engine vehicles.[20] The population is generally demanding more and more mobility: not just in Germany and the EU[21], but also and especially in countries with growing populations and rising economies[22] such as India and China[23].

Worldwide, e-fuels can be used directly in the current fleet using the existing infrastructure. This is a major advantage. The creation of an adequate charging infrastructure for BEVs globally is an even greater challenge than in Germany or Europe. This is especially true for countries in which many people currently have only limited or zero access to electricity. This will lead to vehicles with combustion engines remaining in high demand in many countries around the world.

If we take into account the fact that the majority of new passenger car registrations worldwide will continue to be ICEV in the near future, the gradual introduction of e-fuels will not only reduce

[20] Cf. https://www.bcg.com/de-de/d/press/06Nov2017-PM_The-Electric-Car-Tipping-Point-175834

[21] Cf. Eurostat, passenger cars per 1,000 inhabitants.

[22] Cf. http://www.general-anzeiger-bonn.de/news/wirtschaft/ueberregional/Mehr-Autos-durch-mehr-Pro-Kopf-Einkommen-article3914951.html, "Statistical experience from the economy reveals: when the per capita income rises by 1,000 dollars, the density of passenger cars per 1,000 inhabitants increases by 13 cars."

[23] Cf. Automotive Industry Association, https://www.vda.de/de/themen/automobilindustrie-und-maerkte/markt-international/entwicklung-der-globalen-maerkte.html.

emissions of vehicles that are already part of the global fleet, but also of the majority of future registrations.

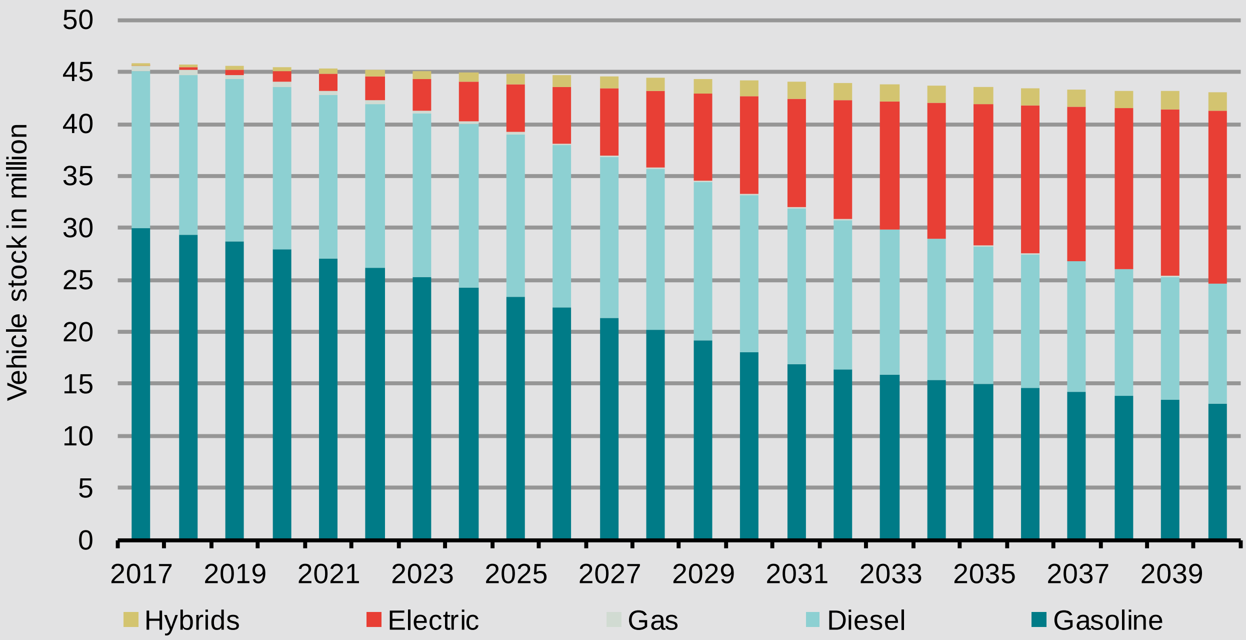
EXCURSUS: E-FUELS AS A POTENTIAL SOLUTION FOR EXISTING VEHICLES

A simplified rough calculation based on figures from the German Federal Motor Transport Authority (2017) shows that even with a very high share of new BEV registrations in the next few years compared to today, the complete replacement of ICEV by 2050 cannot be achieved without prohibitive political intervention (**Figure 30**). In fact, in 2050, not even 50% of cars on Germany's roads would be battery electric , even if

- the total number of new registrations remained at just under 2 million per year; and
- of this number, the proportion of newly registered BEVs stood at 20% between 2020 and 2040 and 50% from 2040 onwards.

This shows that, based on a purely statistical calculation, solutions for de-fossilising transport are needed over and above the exclusive promotion of BEVs. In addition to the case studies listed for new vehicles, where ICEVs with the use of e-fuels could be a further potential solution, the use of e-fuels in the existing fleet is already immediately possible: Whether increasing blended into conventional fuels or prospectively in pure form. The use of e-fuels would prospectively allow the CO_2 emissions of every vehicle currently on the road to be reduced.

Figure 30. Scenario for the development of the vehicle fleet in Germany



Source: Frontier Economics based on figures from the Federal Motor Transport Authority 2017

Technology mix cuts costs, ensures affordability and progression through competition

The costs of

technologies must be taken into account **systemically**

In addition to cost drivers such as energy efficiency, the procurement costs of vehicles, the costs of expanding plants and infrastructures and even the costs of disposing of vehicles and their components have to be taken into account

The use of the existing infrastructure and energy applications, as well as the easy handling and storage properties, means that the use of synthetic fuel and combustibles – in addition to electrification – can save considerable costs in the energy system. These cost savings are offset by certain additional costs:

- Cost savings can be realised, for example, through
  - the use of existing infrastructures such as filling stations, storage, etc.; and
  - the use of existing and less-expensive application technologies such as combustion engines with tanks versus electric engines with batteries.
- Additional investment costs will be generated by
  - electrolysers for producing hydrogen, for example, synthesis units for producing synthetic liquid fuels or methane, and systems for capturing CO_2 (e.g. Direct Air Capture); and
  - generation facilities for renewable energies which must also be set up due to the conversion losses during the production of synthetic fuels and combustibles.

In an assessment of the cost-effectiveness of synthetic fuels and combustibles, it is more than just the conversion losses in the production of e-fuels – which are often at the forefront of the public debate – that are crucial. Instead, the various impacts on investment and expansion requirements in generation, conversion, storage and grids also have to be taken into account.

Renewably produced energy is significantly cheaper abroad!

This can in future be imported in the form of e-fuels

In many regions around the world, renewable energies – in the form of sun, wind, water and biomass – can be produced much more cheaply than in Central Europe. Converted into synthetic fuels and combustibles, these can be used in liquid and gas form in Europe at proportionately low transport costs[24] – and with recourse to the existing pipeline, transhipment, interim storage and tanker infrastructure. Analyses[25] show, for example, that synthetic fuels and combustibles can be produced much more efficiently at locations abroad such as North Africa, the Middle East or Iceland in the long term than through domestic production. For example, synthetic fuels can be made available 30% cheaper via photovoltaics in North Africa than on the basis of offshore wind generation in the North Sea and Baltic Sea.

The use of relatively inexpensive classic vehicles with combustion engines is particularly beneficial for low-income households. The

[24] Our analyses for Agora Energie- und Verkehrswende (2018) show that transport costs account for around 0.5% of the total costs of producing e-fuels. Assuming that gases are transported by tanker (and therefore have to be liquefied and re-gasified), the proportion of transport costs for the production of synthetic fuels in gaseous form is higher at 7% of the total costs – but even here it is still low and in many countries the existing pipeline infrastructure can be used, which is associated with lower costs.

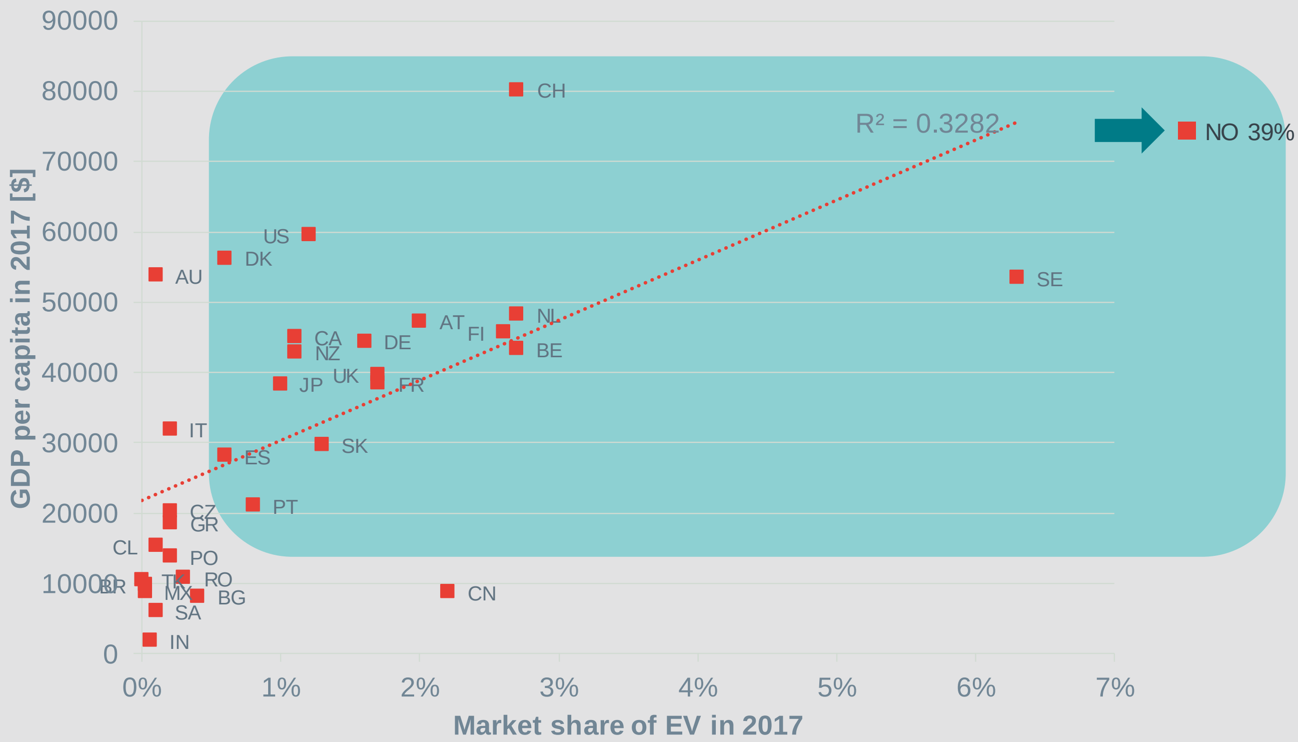
[25] Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018): The future costs of electricity-based synthetic fuels.

customers involved are often dependent on the use of second-hand cars or cheap new vehicles, and at the same time the driving performance required is in many cases moderate. For this population group in particular, it is important to keep the costs of climate-protecting mobility as low as possible and to avoid high procurement investments. This is especially relevant since the share of income that has to be spent on fuel is highest in households with the lowest incomes.[26]

ELECTROMOBILITY IS CURRENTLY ONLY LIMITED TO WEALTHY COUNTRIES

The rise in electromobility is focused primarily – both now and in the foreseeable future – on relatively wealthy countries. This is evident when the per capita gross domestic product is set against the number of electric cars among new registrations (**Figure 31**). The main reasons for this are likely to be the lack of infrastructure in many countries and the high acquisition costs for e-vehicles. In these countries, vehicles with combustion engines will remain in demand for the foreseeable future.

Figure 31. Per capita GDP versus market share of electric vehicles across countries worldwide



Source: Frontier Economics based on data from the World Bank, the International Energy Agency and the European Alternative Fuels Observatory

In practice, there is also frequent re-use in Western Europe of vehicles withdrawn from service, for example in Eastern Europe, and often later also in other regions of the world such as Africa. If this subsequent use is omitted, for example because no charging infrastructure has been developed for electric vehicles in these

[26] Cf. IW (2019), CO_2 avoidance in road transport.

countries, the vehicles' average total life is reduced. On the one hand, this increases the costs of mobility in Germany and Europe, as in third-party states too, and on the other a faster renewal of the overall vehicle fleet is needed. This latter is also associated with a rise in CO_2 emissions since the vehicle production process also generates emissions, and in countries where second and third uses of the vehicles no longer take place, even older and therefore less efficient vehicles will remain on the roads.

6.3 The next steps are crucial

The analysis shows that a transport and energy policy strategy is needed that includes all technology options, including battery electric vehicles, as well as e-fuels, to reduce CO_2 emissions in road transport. However the course for an open and future-focused approach to policies and regulatory frameworks needs to be set now. For this the following steps are necessary:

1. Technologies must be consistently assessed from a bird's eye view, not a ground-up view

In the debate around climate policy, the evaluation of technologies (which also includes vehicle drive systems) needs to consider all impacts on the climate. This means that the evaluation of technologies should extend to cover the climate impact across all phases of the vehicle’s use, across national borders and over the vehicles' entire lifetime.

2. No focus on just one technology –climate policy must facilitate and promote a goal-compliant technology mix

An early commitment to only one technology is neither justifiable from a climate policy perspective, nor can it do justice to the diversity of needs in the reality of consumers' lives. Therefore the climate goals can only be achieved with a mix of technologies.

3. Fair and open regulatory conditions must be guaranteed as quickly as possible

The most promising drive technologies for road transport include battery electric vehicles as well as vehicles driven by e-fuels. Additionally, in Germany and Europe there are possibly vehicles that are driven by hydrogen (fuel cell electric vehicles or hydrogen combustion engine vehicles), synthetic methane (present-day natural gas vehicles) or methanol (e.g. more common in China).

To push all of these options forward, all technologies need to be incorporated into the regulatory frameworks for reducing road transport CO_2 emissions as quickly as possible. This in particular also affects the EU directives. For example, when setting emissions standards for new passenger cars and light commercial vehicles[27], the use of e-fuels should be recognised in line with car

[27] Cf. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019R0631

manufacturers' fleet targets, ideally before the planned review of the CO_2 fleet regulation in 2022/2023. This applies to the passenger car sector as well as to light commercial vehicles. The unequal treatment of e-fuels and electric drives also needs to be changed in the current, revised Directive on Renewable Energies (RED II)[28] in terms of the renewable energy recognition quotas.

National energy programmes, legislative proposals and technical standards (e.g. with regard to the permitted blend-in quotas for e-fuels) must also be adapted in such a way that the use of e-fuels can be expanded. The prerequisites for the market launch and ramp-up of e-fuels must be ensured in this way. This is the only way in which technology-driven competition between promising technologies can exist and lead to the best possible, i.e. most climate-friendly and inexpensive technology mix.

4. Government support programmes need to be opened up for e-fuel projects

At present, the support of new technologies is still essential. This applies to the establishment of battery electric vehicles as well as to e-fuels or other new technology options (e.g. hydrogen).

It has to be ensured that e-fuels are taken into account at European, national and state level in such support programmes. An unilateral support regime (e.g. with a focus on battery electric vehicles) can replace not promoted new technologies and therefore jeopardise the diversity of technologies available. E-fuels should be recognised as a potential solution for a range of applications and therefore not just be used in niche applications. It is a start, for example, that a project for the production and use of liquid e-fuels (in this case green methanol for shipping and heavy goods transport) is being promoted within the framework of the recently selected 20 real laboratories (Reallabore).[29]

5. Innovations in drives, drive technologies and fuels must be embedded in an overall transport policy strategy

In addition to the technologies considered here, there are other transport policy strategies and options available for the necessary CO_2 reductions. These include avoiding traffic, shifting traffic to public transport and rail or intelligent solutions such as car-sharing concepts. Innovations in drive technologies and fuels must therefore be embedded in an overall transport policy strategy. However, it is essential in this context to remember that individual mobility remains a basic need and that constraints to individual mobility is likely to meet little acceptance among broad sections of the population.

[28] Cf. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

[29] Cf. https://www.bmwi.de/Redaktion/DE/Downloads/P-R/reallabore-der-energiewende-gewinner-ideenwettbewerb-steckbriefe.pdf?__blob=publicationFile&v=9

6. Transport and climate policy need to be viewed from a global perspective

The reduction of greenhouse gas emissions is a global necessity. In this respect, it is essential and generally accepted that CO_2 reductions in one region must not lead to rising emissions in other regions, as is the case today, for example, with the relocation of emissions from Europe to China through the import of batteries for BEVs. For an export nation such as Germany especially, it is also important that technology strategies can be used in climate policy not just in Germany or Europe, but in other regions such as Africa. A pure electrification strategy in these countries is inconceivable, since currently there are still 1.6 billion people without steady access to electricity.[30] The production of synthetic fuels and combustibles can be initiated in countries with high renewable energy potential by the industrial nations that are pioneers in this field today, such as Germany. This not only enables medium- and long-term greenhouse gas reductions, but also sustainable value creation in regions that urgently need economic growth prospects.

[30] World Energy Council (2019), https://www.worldenergy.org/PUBLICATIONS/entry/interconnectivity-benefits-and-challenges

ANNEX A DIRECTORY OF ABBREVIATIONS

BEV	Battery electric vehicle
BMWi	Federal Ministry of Economics
CO_2	Carbon dioxide
E-gasoline	Gasoline produced synthetically from renewable energy and a source of CO2
E-diesel	Diesel produced synthetically from renewable energy and a source of CO2
RE	Renewable energies
FCEV	Fuel cell electric vehicle
V	Vehicle
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
LCA	Life cycle analysis / assessment
TtW	Tank-to-Wheel
WtW	Well-to-Wheel

ANNEX B ANALYTICAL METHODS

In this appendix, we explain how we determine the CO_2 emissions for each stage of the added value chain throughout the life cycle in the model.

Essentially, we break a vehicle's life cycle down into four stages:

- the production of the vehicle with focus on the drive systems (cradle-to-gate);
- the generation of drive energy for the drive system used (well-to-tank);
- the use of the vehicle (tank-to-wheel) and
- finally the recycling of the vehicle (end-of-life).

For all four stages, the electricity and energy mix of the country of production or operation represent key influencing factors. These are therefore derived as overarching input parameters for the individual countries over time.

Overarching input factors

Electricity mix

The electricity mix is relevant not just for the vehicle's production, but also for its actual use, and is entered into the model accordingly for all possible production (EU, USA, Japan, China) and operating countries (EU, Germany).

For the model, the CO_2 intensity (or emission factor) of the electricity mix in question is especially relevant. We determine this for Japan, China, the USA and the EU using the World Energy Outlook 2018 (WEO) from the International Energy Agency (IEA). For three scenarios, it estimates both the total amount of electricity generated and the resulting CO_2 emissions, from which the emission factor can be derived. In addition to a reference scenario (the "New Policies" scenario), forecasts are available for an optimistic scenario (the "Sustainable Development" scenario), in which the UN's goals are achieved, and a pessimistic ("Current Policies") scenario, in which the existing laws and regulations are simply continued.

The IEA does not have a separate forecast for Germany. As a result, our analyses in terms of the emission factor are based on the "Long-term scenarios for the transformation of the energy system in Germany", which were drawn up on behalf of the BMWi. At the time the model was created, only reporting module 3, which comprises the basic and the reference scenario (corresponding to the IEA's reference and pessimistic scenario), was available. Accordingly, we have carried out our own estimate for the emission factor of the German electricity mix in an optimistic future scenario (in the same manner as that of the IEA). This is based on the assumption that the ratio of emissions in the optimistic scenario to those in the reference scenario in Germany is identical to that in the EU.

Neither the IEA nor the BMWi take into account emissions from the system expansion needed to provide the planned volumes of electricity from renewable energies. We supplement the approaches taken by the IEA and the BMWi accordingly with these, based on our own estimates following a review of the literature available.[31]

[31] Cf. e.g. Onat, Kucukvar and Tatari (2015), Conventional, Hybrid, Plug-in hybrid or Electric Vehicles? State-based Comparative Carbon and Energy Footprint Analysis in the United States, Supporting Information File I.

Energy mix

The energy mix is also an overarching input factor and is included in a number of places in the model. The energy mix of the country of operation (and not the country of production) is assumed in relation to this in the model for all stages of the analysis. Since Germany and the EU can be selected in the model as the country of operation, we show the energy mix for these two regions. As with the electricity mix, the forecasts for the EU are based on the WEO, while those for Germany are based on the long-term scenarios from the BMWi. We use both sources to determine the emission factor taking account of the overall CO_2 emissions and the primary energy consumption.

As was the case for the electricity mix, there was no optimistic scenario available from the BMWi for the energy mix in Germany at the time the model was created. Accordingly, we have also estimated the emission factor for the German energy mix in an optimistic future scenario. This is based on the assumption that the ratio of emissions in the optimistic scenario to those in the reference scenario in Germany is identical to the ratio of emissions in the optimistic scenario to those in the reference scenario in the EU.

Stages of the analysis in detail

1st stage of the analysis: Vehicle production

The first stage of the analysis in a vehicle's CO_2 life cycle is the production of the vehicle. Emissions at this level come, depending on the drive technology,

- from the production of the drive (i.e. the (e-)engine),
- the storage medium (battery or tank) and
- the bodywork.

The model is fundamentally based on the assumption that one vehicle is required per life cycle, i.e. no wear parts need to be replaced before the vehicle's actual end of life. One exception to this is the battery in battery electric vehicles.

With existing technologies, the battery in a battery electric vehicle can be charged around 1,000 times[32] before it loses capacity (and therefore range) – based on an optimum depth of discharge of 80%. In combination with the capacity of the battery and the consumption per kilometre, this yields a maximum mileage (in kilometres) per battery.

On the model side, it is left up to the user

- nevertheless, to assume only one battery per life cycle (so the hypothetical driver will accept the poorer battery performance and shorter range of the vehicle and continue to use it without replacing the battery),
- to attribute one new battery at scale to the lifetime mileage (this would correspond to the continued use of the battery after the end of the life of the vehicle – for example in another vehicle) or
- to attribute the possibly required second battery fully to the life cycle (this is based on the assumption that the second battery is scrapped together with the vehicle and thus before its actual end of life).

At this point, the user also has the opportunity to make an assumption regarding the depth of discharge, i.e. the driver's charging behaviour. A higher depth of discharge reduces the maximum number of charging cycles and therefore makes earlier battery replacement necessary.

[32] Cf. Peters et al. (2017), The environmental impact of Li-Ion batteries and the role of key parameters – A review, Renewable and Sustainable Energy Reviews 67 (2017) 491–506.

Our estimate of the emissions from battery production is based on the electricity consumption required to produce one kilowatt hour of battery capacity. The emissions from the electricity consumption are then multiplied by the relevant battery capacity.

For all other components in this stage of the analysis, we assume fixed emissions based on data from 2017 and make these dynamic by linking them to the development of the energy mix over time. This dynamisation means that technical improvements and developments that currently cannot be either predicted or quantified can be taken into account. The production of a vehicle in 2025 will therefore cause more emissions than the production of the same vehicle in 2035.

2nd stage of the analysis: Fuel production

In the second stage of the analysis, we consider the emissions generated by the production of drive energy. In specific terms, this means

- for battery electric vehicles: the emissions from the generation of the electricity needed to charge the battery.
- for vehicles with a combustion engine: the emissions from the production of the required volume of gasoline, diesel or synthetic fuel.

The electricity consumption of the battery electric vehicle is calculated directly from the specified consumption per kilometre and the mileage covered per year or life cycle. During charging, charging losses of varying magnitudes can occur. To take these into account, we assume flat-rate charging losses amounting to 20% (based on estimates by the VDI[33]) and adapt the effective electricity consumption accordingly using this factor. In this stage of the analysis, we have not factored in any (potential) additional emissions from the additional expansion of the grid since the extent of the expansion required and the resulting emissions are hard to quantify.

For vehicles with a combustion engine, the emissions per litre of fuel produced are crucial. These emissions are derived from the energy density and the volume of fuel. How many litres of fuel need to be produced overall for a vehicle depends on the third stage of the analysis, namely the vehicle's consumption and its mileage, annual or lifetime.

With conventional fuel, we also assume a bio-fuel ratio of 5% (gasoline) or 7% (diesel) at a flat rate. The lower energy density of bio-fuels is automatically taken into account by the calculation based on the energy content per unit of volume.

The user can select the proportion of synthetic fuels in the overall mix themselves in the control panel.

For emissions from the production of drive energy, we assume a reduction in fuel consumption over time ("efficiency factor").

In this case, the model assumes an annual reduction in fuel consumption of around 1% based on data from the Federal Environment Agency on the historical development of fuel consumption.

In the case of battery electric vehicles, the data for estimating future increases in efficiency is still not very developed due to technology's infancy. Based on forecasts by Agora Verkehrswende[34], we factor an annual efficiency increase of 0.37% into the model.

[33] Fuel cell and battery electric vehicles – importance for electromobility. VDI/VDE study, May 2019.

[34] See Agora Verkehrswende, Climate balance of electric cars, https://www.agora-verkehrswende.de/fileadmin/Projekte/2018/Klimabilanz_von_Elektroautos/Agora-Verkehrswende_22_Klimabilanz-von-Elektroautos_WEB.pdf

These increases in efficiency are only achieved once, depending on the year of purchase, and the car's consumption remains constant over its entire life cycle.

3rd stage of the analysis: Use of the vehicle

Emissions occur only for classical combustion engines in the vehicle use stage. With battery electric vehicles, no CO_2 is produced "tank-to-wheel".

For the combustion engines, as a result of the chemical reactions involved, emissions are produced for each litre of fuel burned. In combination with the consumption of the vehicle type in question, we therefore calculate the emissions per kilometre or annual or lifetime mileage. The assumptions regarding consumption vary for gasoline and diesel vehicles, however they do not change between conventional and synthetic fuel.

Dynamisation is achieved here, as in the previous stage of the analysis, solely through efficiency improvements in fuel consumption since the chemical combustion process in and of itself cannot be changed.

4th stage of the analysis: End-of-life / recycling

The final stage of the analysis is the vehicle's end of life.

Here, we assume a flat-rate value for the emissions produced at the end of the car bodywork's life. This is identical for all drive energies, so it implies indirectly that the bodywork does not differ between the different drive energies. As with the production of individual vehicle components, this is also dynamised in terms of time by being linked to the development of the energy mix.

For the BEV battery, an emission factor per unit of energy (kilowatt hour of battery capacity) is used in the model which, together with the battery size appropriate for the type of vehicle selected, is used to determine the overall emissions. This value is also linked to the energy mix and is therefore dynamised. This procedure is necessary due to the scant data available regarding emissions produced during the disposal or recycling of a vehicle or individual vehicle parts. The recycling technologies used for batteries from battery electric vehicles in particular are not yet standardised. The focus here currently also lies primarily on the recovery of scant resources and less on a process that is as energy-efficient or low-emission as possible.

ANNEX C LIMITATIONS OF OUR ANALYSIS AT THE VARIOUS STAGES OF THE ADDED VALUE CHAIN

Our analysis only goes into a certain level of detail. The simplifications we have made have various impacts on the respective stages of the added value chain:

- in **vehicle production**, we see no efficiency gains in battery production over time or different chemical specifications for the battery. We also (for simplicity's sake) assume that all vehicles within a vehicle class will have the same bodywork.
- For the **generation of drive energy based on renewable energies**, we do consider the emissions for building renewable energy systems (especially solar and wind)[35], but not the emissions associated with the expansion of the charging infrastructure required. Accordingly, emissions from system construction and the transport of liquid fuels are also not factored into our analysis. Essentially, we also assume a constant consumption over the entire life cycle and tank / battery level for all vehicle segments and drives. We also only factor in the country of operation in relation to the electricity mix and not the climate-related or geographical conditions.
- For **vehicle use**, it is also relevant that we do not include any potential rebound effect. Some studies assume that the purchase of a BEV is also associated with a change in how the vehicle is used – for example BEVs tend to be used as a second vehicle rather than replacing old cars. We do not explore this aspect in more detail, however.

With regard to **recycling**, there is so far very little data available (for more on this, see **Analytical Methods**). Due, among other things, to the difficulty of obtaining data, we do not consider any "credits" from material recycling (i.e. the avoidance of future emissions) or second-life uses of individual components such as the battery.

[35] Due to conversion losses from green power to e-fuels, more renewable energy systems are assumed for the sake of simplicity than for the direct use of green power.