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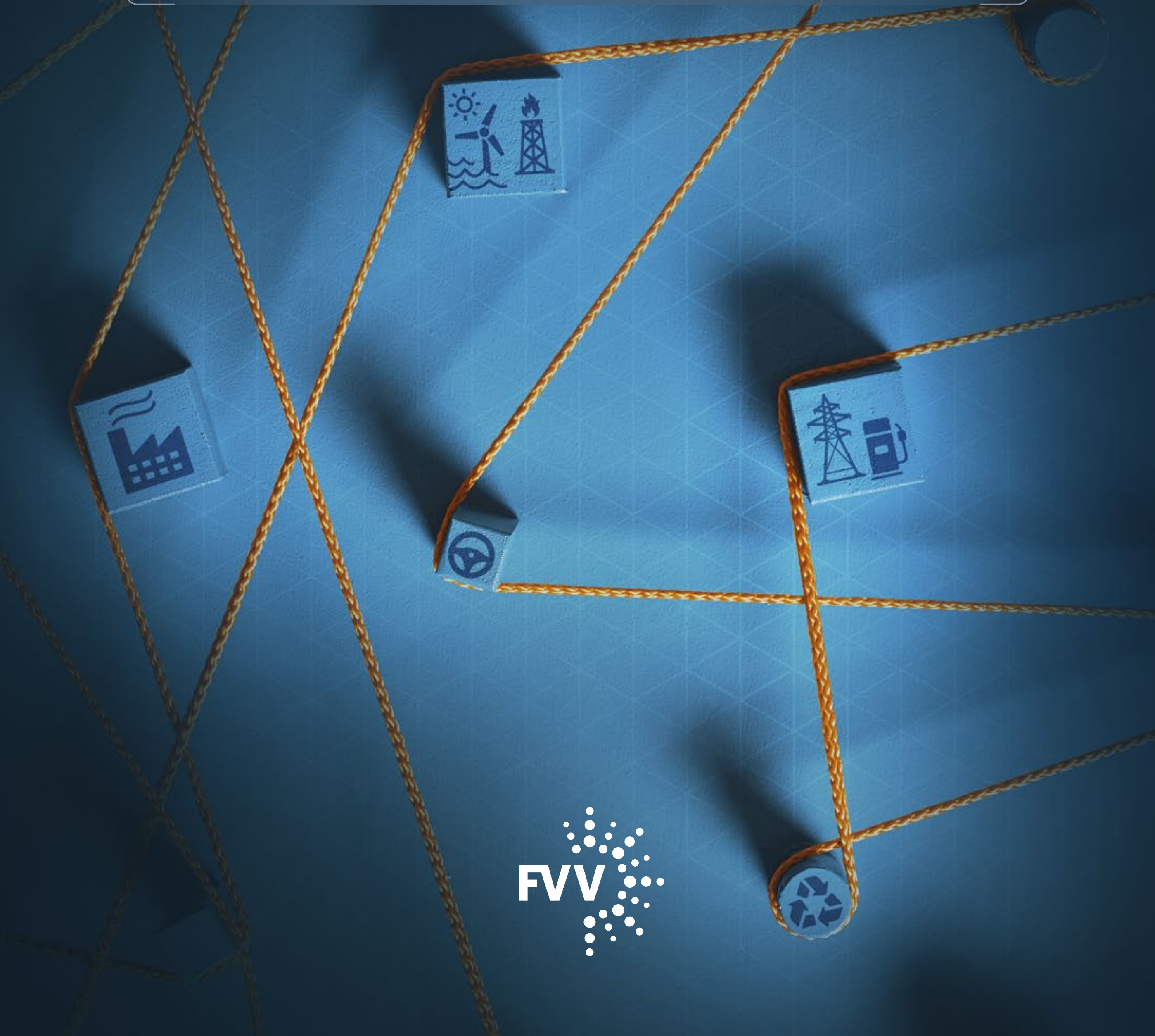
Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector

A Meta-Analysis of LCA Studies on Alternative Powertrain Technologies



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›Well-to-Tank‹
Production, processing and delivery of the drive energy.
›Cradle-to-Gate‹
Production process of the vehicle.
›Tank-to-Wheel‹
Operation of the vehicle.
›Infrastructure‹
Construction and operation of the energy infrastructure.
›End-of-Life‹
Disposal or recycling of the vehicle.

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Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector

A Meta-Analysis of LCA Studies on Alternative Powertrain Technologies

FVV

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What is more environmentally friendly? Keeping an old but functioning refrigerator with a somewhat higher electricity consumption for one or two more years, or replacing it with a new refrigerator belonging to the highest efficiency class? Even such a seemingly banal question can only be clearly answered with the help of a life-cycle analysis that considers all energy and material flows throughout the entire value creation chain – from the extraction of the raw materials, through the production of the components, their assembly and operating period, all the way up to the end of the product life. This is a highly complex matter even for something as simple as a refrigerator. When we look at a car with several thousand components, driven by energy carriers that are produced in large plants and distributed using sophisticated infrastructures, the complexity of a life-cycle analysis increases significantly. Even minor changes to framework conditions, such as the energy mix used for producing the vehicles or energy carriers, can cause the results to fluctuate considerably.

Nevertheless, if we wish to research, develop and realise climate-neutral powertrains and energy carriers for road transport it is not prudent to solely look at the emissions generated during the operating phase; instead, all aspects of the life cycle must be taken into account. After all, the CO_2 that enters the atmosphere through the production of vehicles, plants or infrastructures remains there for longer than the duration of the use phase. As such, it counts towards our remaining global CO_2 budget for achieving the climate targets set out in the Paris Agreement. In politics and business, the general consensus is therefore that a life-cycle analysis is a fundamentally sensible approach. The European Parliament has even requested that the European Commission submits ideas for regulating the passenger vehicle sector on the basis of life-cycle analyses by the middle of the decade. So how do we achieve the balance of considering the presumed inaccuracy of individual analyses, while also benefiting from the general usefulness of life-cycle analyses as a whole?

As a first step, FVV has decided to commission this meta-analysis on existing life-cycle assessments. To this end, the experts from Frontier Economics have analysed more than 80 studies. As virtually all studies work with multiple scenarios, they comprise a total of 430 constellations, corresponding to countless hours of scientifically trained experts. One could also speak of “scientific swarm intelligence” here.

The present meta-analysis initially confirms the assumption that the results diverge strongly. However, if one only observes the 50% of all studies closest to the median, the results are scattered relatively closely. These enable us to compare different powertrains and energy carriers. Here it is evident that although one powertrain technology often prevails over the other in individual analyses, the results in the meta-analysis overlap so strongly that battery-electric cars and diesel vehicles are roughly at the same level even with the current energy mix. If we only consider those scenarios in which renewable energy sources are used during the operating phase – synthetic fuels, green electricity and green hydrogen – the pendulum swings towards the combustion engine driven with synthetic fuel. Another important finding from the meta-study is that the necessary investments in the energy infrastructure were ignored in almost every case. Likewise, the plug-in hybrid powertrains that are successful in the market are rarely included in life-cycle analyses.

Therefore, there is plenty to be done before life-cycle analyses can become a standard tool for evaluating future powertrains and energy carriers. As a result, it is not wise to make premature reactions on the basis of the results of individual studies.

We hope this new FVV study makes for exciting reading and would be delighted if you discuss the results with us!

Frankfurt/M. | in June 2020

Executive Summary

»Climate protection in the mobility sector requires a comprehensive, sustainable approach.«

In the context of the Paris agreement the European Union and Germany have set themselves **ambitious climate protection targets** that involve reducing annual CO2 emissions in all energy-consuming sectors. In an effort to make this target tangible and measurable, the European Union and Germany have **translated** it **into annual targets**; i.e. by 2050, the EU's annual emissions need to be reduced by 80-95% compared to 1990. Germany has also set an interim target for 2030, when annual emissions need to be 55% lower than in 1990.

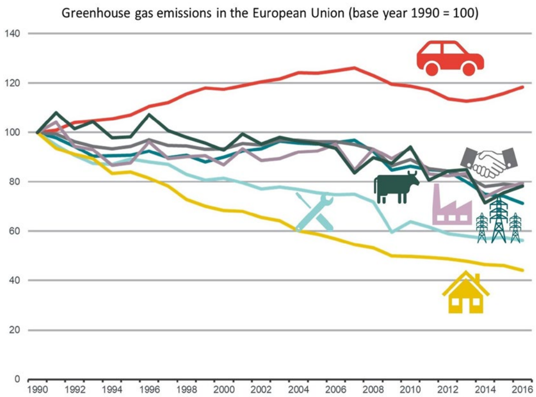

Figure 1: Stagnating transport sector emissions

This target has been **further broken down** by the German government into individual **sector targets** for energy, buildings, transport, industry, agriculture, land use and forestry sectors. For example, the transport sector emission target for 2030 is 40% lower than 1990. However, despite efforts to save drivetrain-specific CO2 emissions, by using more efficient engines for example, the sector remains unable to demonstrate annual sector-wide emission reductions, because specific emission savings have been more than outweighed by increasing demands for mobility (see **Figure 1**).

Stagnating transport sector emissions have sparked a fierce political discussion around possible concepts and technologies to achieve the sector-specific target in 2030, which often neglect the CO_2 impact of technologies in other sectors, countries or years. However, given the global challenge of climate warming, emissions must be measured comprehensively across the entire life cycle of a technology to assess its true climate impact.

1 Emissions are allocated to individual sectors based on the source principle, i.e. to the "producing" sector rather than that in which the product is used.

»For global challenges, we need to look beyond national and sectoral targets to the bigger picture.«

Breaking down global targets into more specific objectives at a national and sector level may seem a sensible way forward from a political perspective, given that it defines milestones clearly and measurably. However, it also promotes thinking within limited geographical or sectoral borders, which may jeopardise efforts to achieve climate protection targets cost-efficiently, or, in extreme cases, at all.

With the above in mind, an intensive energy-policy debate has arisen around concepts and technologies – both regarding the powertrain (combustion engine or electric) and the type of energy sources used (electric, liquid, gaseous) – to ensure road traffic achieves its climate protection targets effectively. Numerous studies have tried to analyse the climate impact of technologies across the life cycle, albeit with varying focus and detail variants, which makes it difficult to derive a comprehensive overview.

The **objective of the study** is therefore to examine available international studies and their results but also their "white spots" on the climate impact of different powertrain technologies over the entire life cycle in a meta-analysis.

»Annual, national, sector-specific considerations are not well placed to tackle the global challenge of climate warming.«

Climate protection policy is a direct consequence of the IPCC findings, which concluded that limiting a further increase in the global temperature to 1.5°C above pre-industrial levels would only allow for a **remaining budget of CO_2eq** between 420 to 580 Gt CO_2eq that can be emitted into the atmosphere (see **Figure 2**). It is important to note, therefore, that any meaningful technological choice has to be evaluated against its contribution to utilise this remaining budget effectively.

This requires a system analysis based on a cross-sectoral, global and temporally unlimited system boundary:

- **Emissions must be minimised across all sectors.** To ensure technologies can be comprehensively compared, all emissions generated by a vehicle in other sectors should be attributed to the vehicle.
- **The climate impact is global.** In the context of the greenhouse effect, the geographical location at which emissions are generated is irrelevant.
- **The climate impact of CO_2 is not time-related.** If the climate target of limiting global warming to 1.5 or 2°C is taken seriously, there is only a certain amount of greenhouse gases left worldwide (i.e. a certain emission budget, in the following referred to as "budget principle"). This means that all emissions are relevant – regardless of when emitted.

However, many climate policy measures are limited to a specific time, geography and/or sector (see **Figure 3**): EU fleet targets, for example, are only valid within the European Union and national measures are typically even more limited. Moreover, the EU fleet targets focus only on one very specific life-cycle stage, i.e. vehicle use. Emissions generated by a vehicle in energy and industrial sectors are not considered in this context.

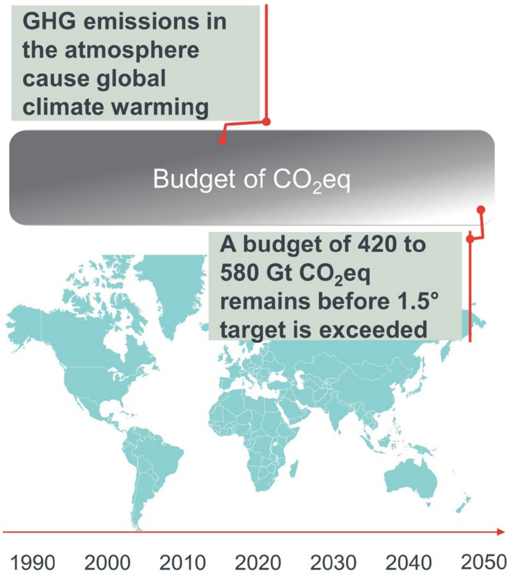

Figure 2: The global budget for CO_2eq is limited

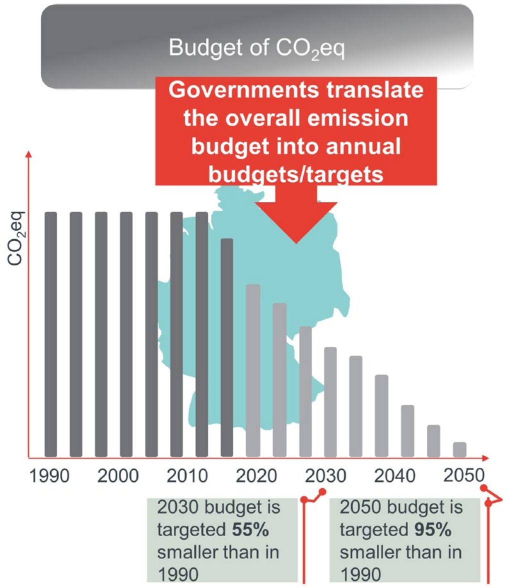

Figure 3: Governments translate budget into national, annual targets

»Accordingly, choosing technologies sustainably requires a comprehensive cross-sectoral, global and intertemporal life-cycle analysis.«

To meaningfully evaluate technological options in terms of their climate and further sustainability effects, all direct and indirect effects throughout all upstream and downstream stages of the value chain must be considered: The perspective has to be extended towards a comprehensive life-cycle analysis for all phases of a product‘s life.

Limiting the perspective to a specific portion of the life cycle like the use phase of a vehicle can spawn the undesired outcome that technologies appear superior, which – in a broader context – do not elicit overall emission savings – simply because emissions are lower within the narrow sector-specific, geographical and temporal perspective.

With this in mind, applying a comprehensive analysis that captures all emissions across the entire life cycle of a technology is a must (see **Figure 4**).

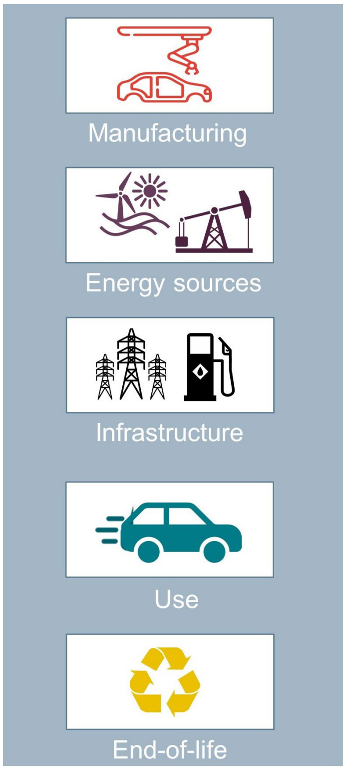

Figure 4: Life-cycle phases

Besides

- the pure use of the vehicle (tank-to-wheel),

this encompasses particularly:

- The manufacture of the vehicle (cradle-to-gate),
- The provision of the drive energy (well-to-tank),
- The build-up and operation of the necessary infrastructure (infrastructure) and
- The recycling of the vehicle to recover raw materials (end-of-life).

The single life-cycle sections can be subdivided almost indefinitely, which means on the one hand that reliable statements on the advantages of single drive options regarding climate protection targets are impossible unless the complex interferences illustrated above are considered. Conversely, researchers face pragmatic limitations and may try to consider these extensive effects at least at an aggregated level.

»A large database is available, but still lacks key information.«

For this meta-analysis we have identified and reviewed more than 80 studies that examine the life cycle CO_2 impact of vehicles and powertrain (or parts thereof).

We find that despite the large dataset, **important information is still missing:** While some life-cycle phases like vehicle manufacture and use are covered by most studies, end-of-life emissions are more rarely covered and almost no study investigates the need for infrastructure expansion and related emissions. Further, while most studies consider certain powertrain technologies (such as battery electric vehicles, BEVs and internal combustion engine vehicles driven with diesel or gasoline, ICEVs); other technologies are rarely covered (such as vehicles driven with natural gas, hydrogen, e-fuels generated from renewable electricity, for example fuel cell electric vehicles, FCEVs or ICEVs).

Further, **comparability remains a major challenge**: There are numerous application cases in individual road transport and each underlying parameter drives the overall emission impact of a vehicle. Parameters include mileage, frequency of use, size of the car and load: For example, the climate footprint of a commercial vehicle with annual mileage exceeding 50,000 km per year will evidently differ completely from that of a commuter car driven only a limited distance each day. Application cases and their respective emission impacts are further differentiated by parameters such as climatic region and topology.

Individual study results can only be generalised to a limited extent given the enormous variety of application cases.

However, when studies compare different technologies, the result can only be based on a specific application case with the respective underlying parameters. Most studies consider a generic application case, but relatively few consider other, yet common, application cases that involve other car sizes and driving behaviours etc. Therefore, individual study results can only be generalised to a limited extent.

»From a climate protection perspective, no single technology comes out on top, but CO_2 emissions occur at different life-cycle phases.«

Available studies show a very heterogeneous picture regarding overall CO_2 emissions arising from different alternative drive options in the traffic sector. **Figure 5** summarises the distribution of results across evaluated studies and life-cycle phases for the most frequently examined technologies: BEVs driven with electricity for charging available in the respective country and driven with 100% renewable electricity for charging, ICEVs driven with diesel and gasoline and the respective e-fuel generated from renewable electricity and FCEVs driven with hydrogen (H_2) generated both from a mix of sources like natural gas and from renewable electricity via electrolysis.

Overall, **no technology comes out clearly on top**. Life-cycle analysis prove that CO_2 emissions are similar for many available powertrain technologies. However, the very significant variation in the result is driven by both **uncertainty** and the varying application cases.

Emissions differ significantly between the **different life-cycle sections** of the available technologies. Vehicle manufacturing and well-to-wheel emissions, i.e. drive energy manufacturing and vehicle use, are the largest emission drivers. Vehicle manufacturing is across all studies typically larger for BEVs and FCEVs than ICEVs, but BEVs tend to be advantageous from well-to-wheel.

Consequently, **individual assumptions** and specific underlying conditions determine which technology is the most advantageous with no overarching trend.

There are also indications as to how, in future, **all technologies** will be able to significantly reduce their emission impact and even become climate-neutral. This is possible if “green” drive energy is used, i.e. electricity for charging, H_2 and e-fuels all generated from renewable energy sources.

Research gaps include both life-cycle phases and technological options.

Our meta-analysis nevertheless also identified several remaining **research gaps**/white spots:

- Few studies investigate **end-of-life** emissions in detail. However, a more accurate CO_2 estimate would be particularly interesting, since the direction of impact for end of life could go both ways – namely, both emissions or emission savings.
- No study considers energy **infrastructure** emissions in a vehicle’s life-cycle analysis. However, after analysing some specific studies we deduced that infrastructure emissions may well comprise a share approaching 10%[2] of total vehicle emissions. Accordingly, these emissions should not be neglected and would require further analysis.
- The coverage of the full breadth of available **technological options across such studies** is quite unbalanced: Generally, all types of e-fuels are hardly captured and studies also rarely examine FCEVs and combined powertrains like hybrids.

2 We conservatively calculate a bandwidth of 5 to 8%.

Figure 5: Based on CO_2 life-cycle analysis, no single technology is superior

Note: To ensure a rough comparability, study results have been scaled to a life mileage of vehicles of 150,000 km.

»Technology-open and target-oriented approaches in climate policy can ensure effective CO_2 emissions.«

To date, we have discussed the following:

- That any climate policy decision targeting individual technologies must first consider **comprehensive analysis** so that technologies can be chosen sustainably (see **Chapter 2** Motivation and Approach, as per section "Choosing technologies sustainably requires a comprehensive cross-sectoral, global and intertemporal life-cycle analysis");
- That unfortunately, such a comprehensive **database** is yet **not fully available** (see **Chapter 2** Motivation and Approach, as per section "A large database is available, but still lacks key information"); and
- What is already available indicates that there is **no clear superior technology**, but the relative advantages of powertrain technologies depend instead on very individual circumstances (see **Chapter 3** Results).

Nevertheless, **climate policy** needs to address the challenge of global warming now. The combined findings of the reviewed studies – despite several limitations mentioned – still allow for some early conclusions on policy recommendations:

- **Incomplete information demands a target-oriented and technology-neutral policy approach:** Many parameters depend on individual use cases, making them unsuitable by nature for central decision-making. In addition, it must be assumed that many technologies, mobility behaviour and further underlying conditions will change in future and many developments will remain unpredictable. Accordingly, any technology-specific decision today bears a significant risk of being proven wrong in future and the major recommendation to policy makers is to design instruments in a technology-open way.
- **One-off vehicle emissions combined with a long lifetime require special consideration of temporal dimensions:** Policy efforts to reach specific targets such as the 2030 target for the German transport sector can – with a limited perspective – result in atmospheric emissions out of budget (see **Figure 6**). This may especially happen when a reduction in annual transport emissions (e.g. tank-to-wheel) requires large one-off-emissions in previous years (such as vehicle manufacturing emissions). The example in **Chapter 4** Conclusions stresses the importance of temporal dimension and recognition of the budget principle regarding climate targets.
- **Sectoral targets might incentivise emission shifts rather than genuine emission reductions.** The exemplary calculation shows how a policy measure – ideal for reducing annual transport sector emissions – adversely affects e.g. industrial and electricity sectors, underlining the importance of a cross-sectoral perspective as well as the temporal dimension.

In sum, **a bird‘s eye view and technology-open approach** is required.

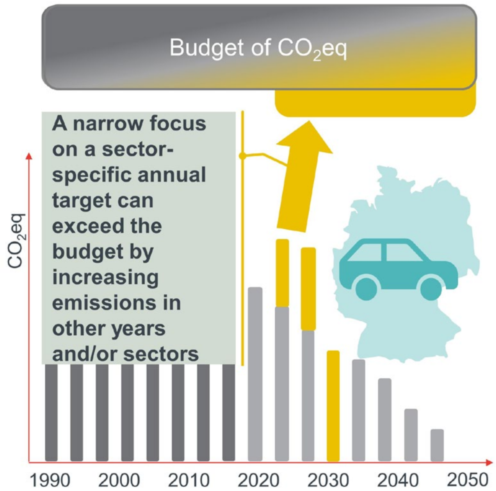

Figure 6: Temporal dimension is key with large one-off emissions

Motivation

Based on the Paris Climate Protection Agreement, Germany and the European Union have set themselves the ambitious target of reducing greenhouse gas emissions (CO_2eq, CO_2) by 80-95% by 2050, compared to 1990 levels. Accordingly, the Federal Government's Climate Protection Plan 2050 provides an interim target for 2030, namely reducing CO_2 emissions by at least 55% compared to 1990. This target has been broken down into individual targets for energy, buildings, transport, industry, agriculture, land use and forestry sectors[3].

The transport sector – and road transport in particular – are attracting increasingly strident debate and the ever-growing demand for mobility has outweighed numerous efficiency increases within the transport sector (see **Figure 7**). Mobility has contributed to and/or been driven by economic growth in many other sectors, reflected in today's growth in mobility usage in absolute terms. Again in absolute terms, this explains why CO_2 transport sector emissions have not decreased compared to 1990 levels (see left side of **Figure 7**). In light of this historic trend, the target set by the German government to reduce transport sector emissions by 40% by 2030 seems particularly ambitious.

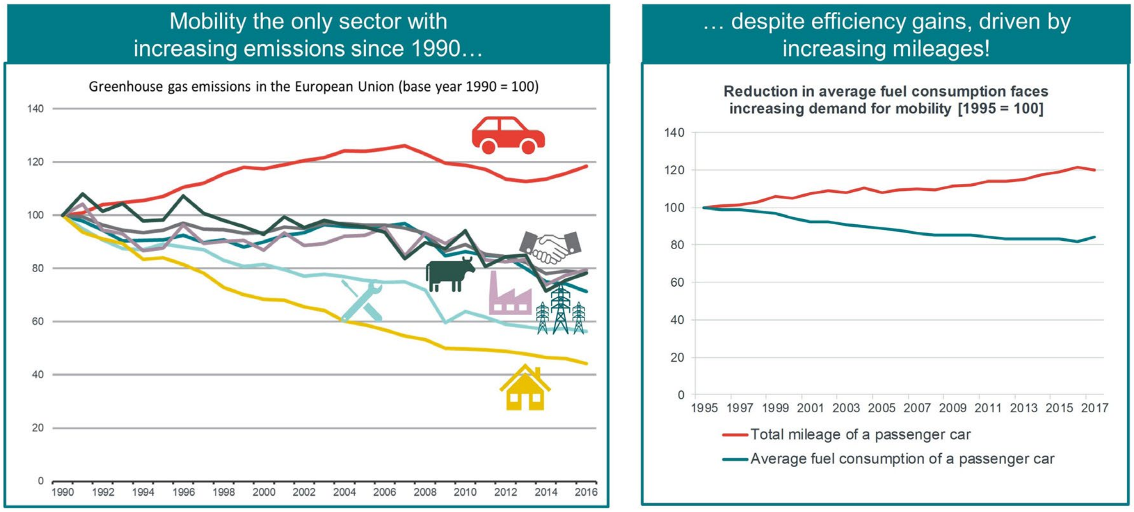

Figure 7: Emissions in the mobility sector have been increasing despite efficiency gains

3 The allocation of emissions to the individual sectors is based on the source principle, i.e. emissions are allocated to the "producing" sector rather than that in which the product is used.

»For global challenges, we need to look beyond national and sectoral targets to the bigger picture.«

Breaking down global targets into more specific aims at a national and sector level may seem a sensible way forward from a political perspective, given that it defines milestones clearly and measurably.

However, it also promotes a mindset limited to specific geographical or sectoral borders, which may jeopardise achieving climate protection targets cost-efficiently, or, in extreme cases, at all. It may also be that CO_2 reduction measures in one sector guarantee a maximum reduction in CO_2 emissions for this specific sector. However, emissions elsewhere may not be reduced or even increased by these measures, meaning that across all sectors, overall CO_2 emissions remain more or less constant. Especially in view of increasing sector coupling, it is questionable whether the overall targets can be achieved cost-efficiently if each sector only pursues its own targets.

Not only in view of achieving the superior targets of the Paris Agreement but also from a sustainability perspective[4], it is important to remember that CO_2 emissions and reduction strategies have a global effect. Accordingly, while a one-sided geographic emission relocation into other regions (inter alia via relocation into upstream or downstream steps) may help achieve individual national political targets, this does not mean that it will contribute to climate protection and/or sustainability aspects (e.g. human rights protection or water saving) at a global level.

With the above in mind, an intensive energy-policy debate has arisen around concepts and technologies – both regarding the powertrain (combustion engine or electric) and the type of energy sources used (electric, liquid, gaseous) – to ensure road traffic achieves its climate protection targets effectively. This has prompted an increasing focus on emissions and other effects related to sustainability due to different mobility technologies besides the clearly visible effects related to the actual vehicle use phase, alongside the whole life cycle of technologies.

In this context, FVV has asked Frontier Economics to carry out a meta-analysis and evaluation of available international studies on the climate footprint of different powertrain technologies for the entire life cycle of vehicles (from cradle-to-grave or cradle-to-cradle, see **Chapter 2**).

4 In 2015, the United Nations issued the Agenda 2030 for sustainable development and committed itself to meeting 17 global targets for a better future. Climate protection is one of the 17 targets.

»Our objective: To comprehensively review life-cycle analysis for powertrain technologies.«

To do so, we analysed more than 80 studies with nearly 500 scenarios[5] (most from the past 15 years and with a German or European focus), which examine all or selected sections of a life-cycle analysis of CO_2 emissions of powertrain technologies, i.e. vehicle production, fuel production, energy infrastructure, usage and end-of-life. Analyses of different components (e.g. batteries or single infrastructure components) will additionally be considered where otherwise no data at all exists. Aims include:

- First, to conclude what can be assumed as safe knowledge, where large areas of uncertainty or even “white spots” exist.
- Second, based on the available study results, we will draw a conclusion concerning the advantages of single powertrain technologies.

Thereby, we consider the fact that emissions must be considered across all sectors, for all regions and intertemporally.

The study is structured as follows:

- First, Chapter 2 Motivation and Approach, as per section "Choosing technologies sustainably requires a comprehensive cross-sectoral, global and intertemporal life-cycle analysis", explains which aspects need to be considered to conduct a life-cycle analysis of CO_2 emissions of different powertrain technologies comprehensively.
- Chapter 2 Motivation and Approach, as per section "A large database is available, but still lacks key information", outlines the available literature and the challenges of comparability and completeness of different studies, while
- Chapter 3 Results presents the findings of our meta-analysis in more detail for each section of a vehicle’s life cycle.
- Finally, in Chapter 4 Conclusions and formulate policy recommendations.

5 A scenario comprises a technology (e.g. BEV, ICEV diesel) and assumptions regarding the electricity mix, hydrogen production method and vehicle size in particular.

Choosing Technologies sustainably requires a comprehensive cross-sectoral, global and intertemporal life-cycle analysis

To meaningfully evaluate technological options regarding their climate effects and further sustainability effects, it is essential to consider all direct and indirect effects at all upstream and downstream stages of the value chain: The perspective has to be extended towards a comprehensive life-cycle analysis for all product life phases. Regarding the ultimate objective of establishing a circular economy, even recycling and reintroduction into the raw material cycle is part of the relevant scope.

It is imperative that climate policy measures are considered across sectors, globally and without time limits.

»National, sector-specific considerations give only little insight into the effects of a technology.«

This requires a system analysis that is based on a cross-sectoral, global and temporally unlimited system boundary (see **Figure 8** for an illustration):

- **Emissions must be minimised across all sectors.** To ensure a comprehensive comparison of technologies, all emissions caused by a vehicle in other sectors – e.g. in the energy sector during production of the drive energy or the industry sector during the manufacturing of the vehicle – should be attributed to the vehicle. Focusing only on the transport sector is not very meaningful when it comes to achieving total emission targets – especially in the context of a debate around sector coupling.
- **The climate impact is global.** This means that for the greenhouse effect, where emissions occur is irrelevant. Consequently, emissions considered should not be restricted to those arising when a vehicle is produced in Germany or in the EU but should rather be extended to those arising in supplier countries like China. National targets – for example those laid down in the Kyoto Protocol or the Paris Convention – should therefore also be critically viewed since emissions can be imported or exported. If targets to reduce greenhouse gas emissions differ in severity, there will be an incentive to relocate emission-intensive processes to less regulated countries instead of minimising overall emissions.

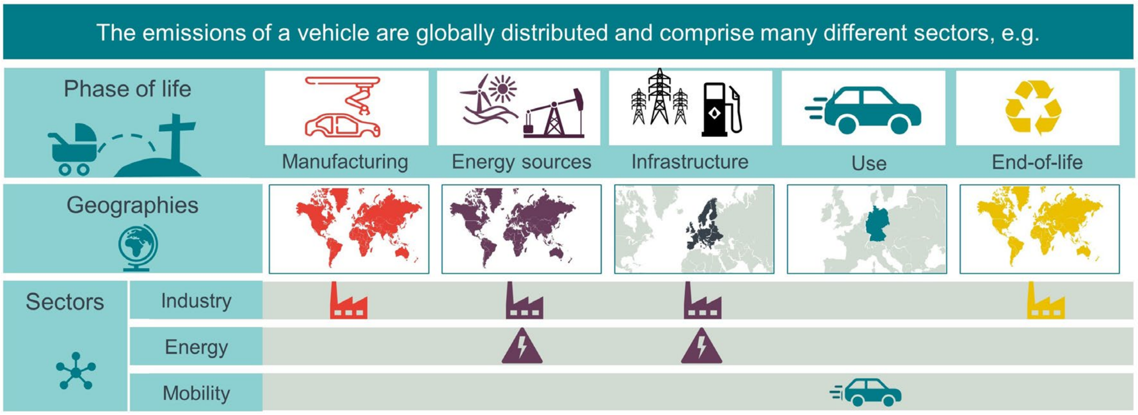

Figure 8: National, sector-specific considerations reveal little insight into the effects of a technology

- **The climate impact of CO_2 is unrelated to time.** When it comes to emission savings, ultimately relevant emission quantities are expressed by the stock of absolute and cumulative CO_2 emissions: If the climate target of limiting global warming to 1.5 or 2°C is taken seriously, only a limited amount of greenhouse gases is left worldwide (i.e. a certain emission budget, hereinafter referred to as a "budget principle"). This means that all emissions are relevant – independent of when emitted. The positive correlation between cumulative human-induced CO_2 emissions since 1876 and temperature change from 1850-1900 is illustrated in **Figure 9**.

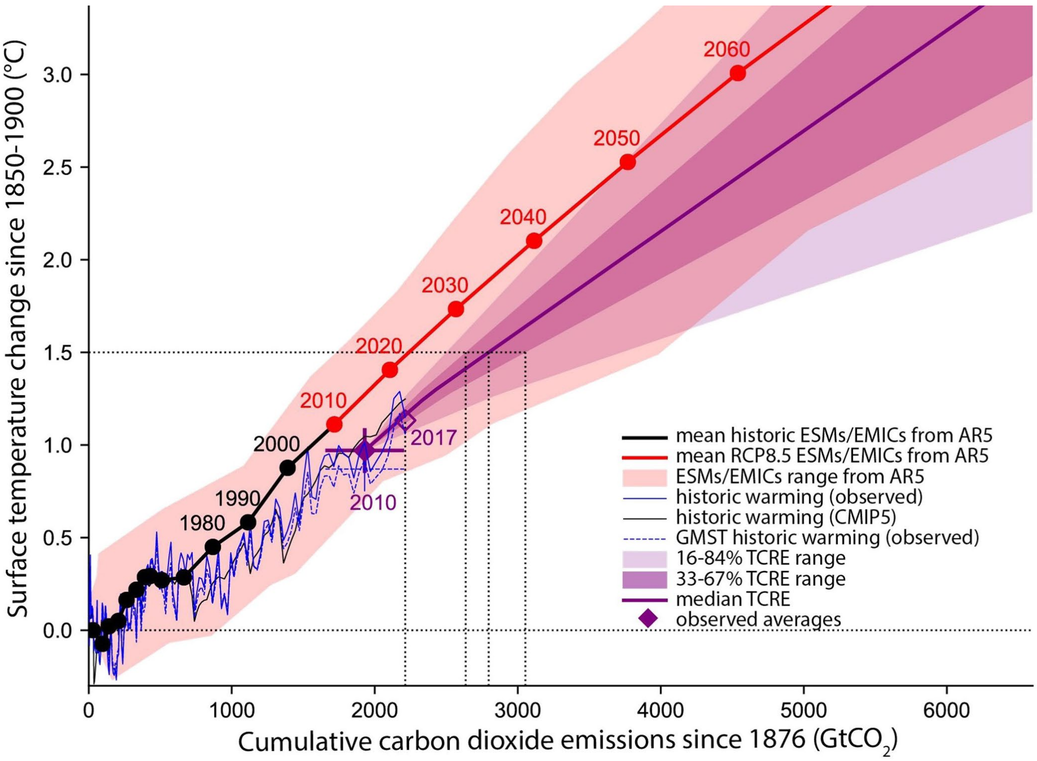

Figure 9: IPCC climate models show a direct correlation between accumulated CO_2 emissions and temperature increase

However, many climate policy measures are limited to a specific sector, geography and/or time: The EU fleet targets for example are only valid within the European Union and national measures are typically even more limited. Moreover, the EU fleet targets only focus on one very specific life-cycle stage, i.e. the use of the vehicle. Emissions generated by a vehicle in the energy and industrial sectors are not considered in this context.

Instruments that only affect parts of the entire life cycle of a technology create disincentives as they often treat a simple shift of emission equal to true emission reductions!

Limiting the perspective to the mere use of the vehicle can lead to disincentives that are out of step with climate policy. It is quite possible, for example, that such instruments will promote technologies which, in the broader context, show no better overall climate impact – simply because emissions are lower within the narrow sector-specific, geographical and temporal perspective. Instruments that only impact on parts of the entire life cycle of a technology will unjustifiably place emission relocations and emission avoidances on the same level!

»With that in mind, any effective climate protection measure must be based on a comprehensive technological analysis.«

In **Figure 10** we illustrate the vast number of different life-cycle sections that must at least be considered to allow for a true comprehensive analysis that spans from cradle-to-grave or even cradle-to-cradle. Besides the actual use of the vehicle (tank-to-wheel), this encompasses especially

- The manufacturing of the vehicle (cradle-to-gate),
- The provision of the drive energy (well-to-tank),
- The build-up and operation of the necessary infrastructure (infrastructure) and
- The recycling of the vehicle to recover raw materials (end-of-life).

The figure also shows how CO_2 emissions of single life-cycle sections are attributed to the different sectors (industry, energy, transport), underlining our finding that today's sector-related focus of climate policy measures largely ignores these cross-sectoral contexts.

The single life-cycle sections can be branched out almost indefinitely wide and the branches in **Figure 10** were only cut off for pragmatic reasons. Accordingly, study authors also face the challenge of considering these extensive effects, at least at an aggregated level, because reliable statements on the advantages of single powertrain options regarding climate protection targets cannot be made without taking the complex interferences illustrated above into consideration.

Finally, any meaningful evaluation of technological options should potentially also include further sustainability effects. If one powertrain technology is favourable in view of CO_2 emissions, this does not necessarily mean that the conclusion is the same regarding other sustainability targets. Further aspects, which need to be taken into account at least anecdotally, include, for example, land use for RES, local emissions from vehicle usage or risks of methane leakage (see for further examples **Figure 10** “Further anecdotal environmental effects”).

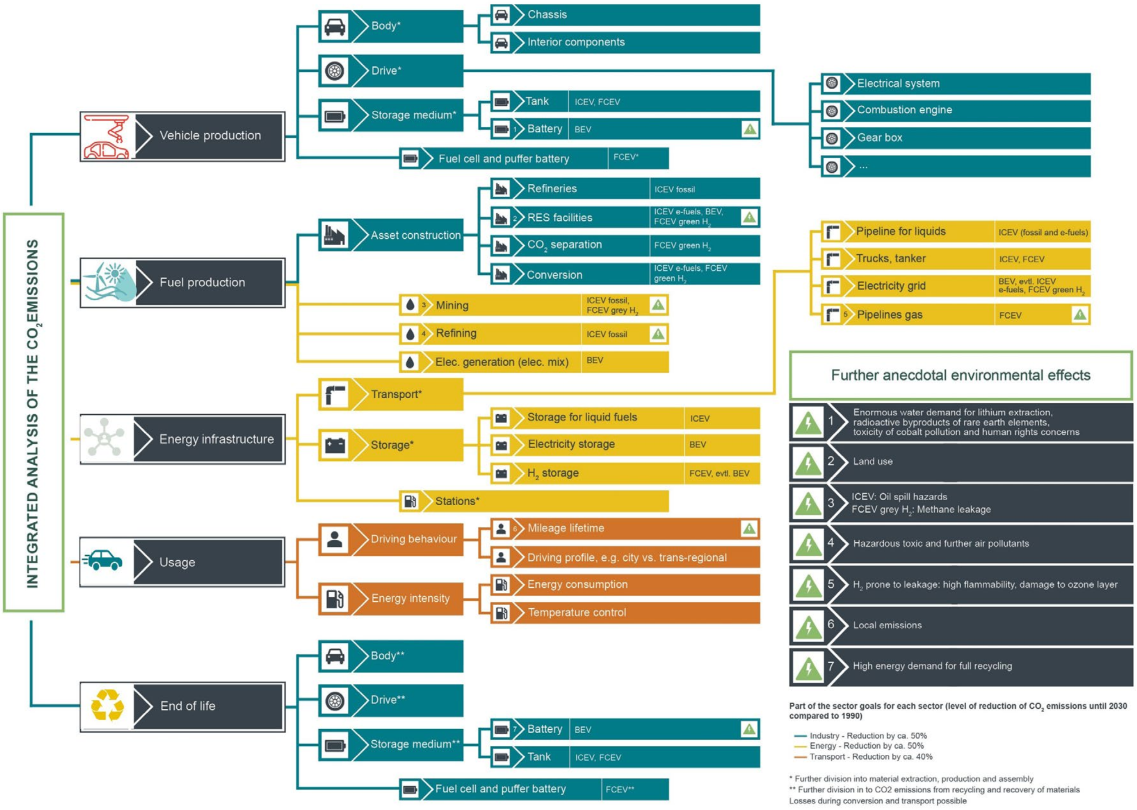

Figure 10: A comprehensive analysis of the CO_2 footprint always requires a detailed observation of all sections of the life cycle and of all effects on upstream and downstream sectors

A large database is available, but still lacks key information

The comprehensive consideration of technologies described is nothing new; it has already been established under the heading "eco-balance" and is even defined by relevant standards (e.g. ISO 140). Consequently, there is potentially a large database and ample studies available that can be used to compare powertrain solutions.

This comprehensive analysis is often interpreted in existing databases and studies, however, in a narrower sense than illustrated in **Figure 10.** Consequently, establishing a meta-analysis requires answers to the following:

- What is the international state of research for all stages of value-adding for drive concepts relevant to the respective life cycle?
- What can be assumed as safe knowledge and where do considerable uncertainties lie? Have all relevant advance effects been taken into consideration or do any "white spots" still exist?
- Where will further research be needed?
- What can be said about the advantages of single powertrain concepts, based on the available study results?

»An extensive database elicits a wealth of information.«

For our meta-analysis, we identified 85 studies that investigate (part of the) aspects of a life-cycle analysis of CO_2 emissions of powertrain technologies for passenger cars[6]. Accordingly, we focused on thematically relevant powertrain technology studies. Analyses on different components (e.g. batteries or single infrastructure components) were additionally considered where no data existed otherwise. Most of the studies are from the past 15 years – as illustrated in **Figure 11** – since alternative powertrain systems (such as BEVs or FCEVs) have only come to the fore in recent years. Furthermore, we emphasise studies with a German or European focus.

6 See Chapter 6 "life-cycle analysis considered in our meta-analysis" for an overview of the single studies taken into account.

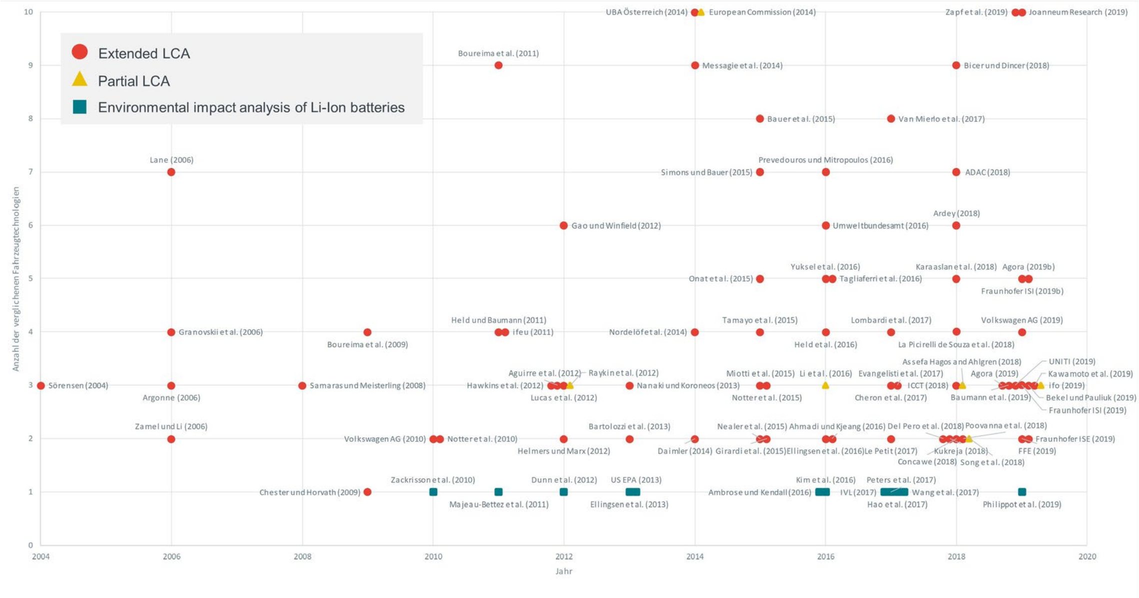

Figure 11: There are comprehensive sources with a large database available – our meta-analysis focuses on 85 international studies from the past 15 years

Note: The reviewed studies include nearly 500 analyses, (e.g. with different electricity mixes, hydrogen production methods, vehicle sizes) with up to ten different technologies (e.g. BEV, ICEV diesel, ICEV gasoline).

»Despite the large dataset, none of the studies really covers all the relevant aspects in full detail.«

Despite a large available database as shown in **Figure 11**, we note that none of the studies considers all five life-cycle phases we identified as relevant for any meaningful analysis (i.e. vehicle manufacture, manufacture of the drive energy, energy infrastructure (extension), vehicle use and end-of-life). Particularly prominent is the exclusion of energy infrastructure to provide energy from life-cycle analysis for vehicles (see **Figure 12**), which is possibly attributable to the abovementioned narrower interpretation of the term “eco-balance” and the standards defined therein. When leveraging a comprehensive life-cycle analysis to underpin meaningful climate policy decisions, however, all emissions associated with the energy infrastructure need to be considered, i.e. the establishment of charging pillars, hydrogen filling stations and networks as well as losses arising from transport, storage and energy conversion.

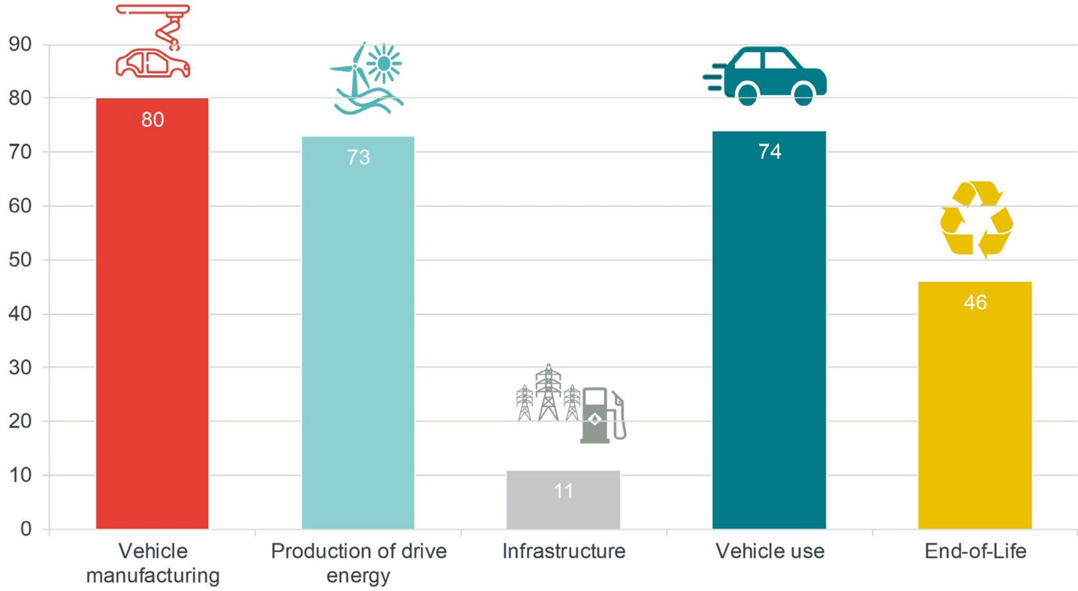

Figure 12: Energy infrastructure is regularly excluded from life-cycle analysis (n = 85 studies)

Note: In some of the life-cycle analysis, infrastructure comprises manufacturing and road operation emissions. Since these are identical for all vehicle types, roads are no longer taken into consideration in this study. However, these studies are included in the infrastructure bar.

»Comparability and completeness remain a core challenge.«

The transport sector includes a wealth of variety in the possible appliance cases, where many underlying conditions affect the technology emission footprint: For example, the climate footprint of a commercial vehicle with annual mileage exceeding 50,000 km per year will evidently differ completely from that of a commuter's car driven only a limited distance each day. The same applies to parameters such as load, size, climate, range or the type of drive energy used (power mix, share of biofuels etc.).

Their dependence on assumptions and scenarios makes it difficult to generalise study findings.

However, a specific result of the **comparison** between technologies can only be based on a specific application case with the respective underlying parameters. Most studies, for instance, consider generic application cases involving maximal mediumsized cars, such as a VW Golf, a limited range requirement, average outside temperature etc. Accordingly, relatively few studies consider other, yet common, application cases that involve e.g. larger cars with higher payload, or more realistic geographical situations or temperatures. Therefore, the generalisation of individual study results is only possible at a very limited extent.

Moreover, many technological options available today can help reduce CO_2 emissions of the transport sector. Savings can, for instance, be realised by boosting powertrain efficiency or switching from fossil to CO_2-neutral energy carriers. One of these CO_2-neutral energy carriers is renewable electricity charging, but also e-fuels – i.e. liquid fuels[7] and gases such as hydrogen produced from renewable energy sources – rank among this type of energy carriers. Consequently, there are numerous powertrain types available, e.g. battery electric vehicles (BEVs) or highly efficient combustion engine vehicles (ICEVs) driven with fossil fuels, biofuels or e-fuels, sometimes combined with hybrid vehicles or fuel cell electric vehicles (FCEVs).

Accordingly, ensuring **complete** coverage of all relevant technological options becomes increasingly challenging, which explains why the degree of detail in which individual technologies are reviewed varies significantly:

- While certain powertrain technologies have attracted significant attention in recent analyses, other technologies are rarely covered: Powertrains, like BEVs or ICEVs, are widely analysed, and others – e.g. liquified petroleum gas vehicles, compressed natural gas vehicles and plug-in hybrid electric vehicles – only sparsely (see **Figure 13**).
- Generally, no study covers the wide-ranging fuel options offered by a specific powertrain (e.g. an ICEV powertrain offers scope to apply either fossil, bio or renewable electricity-based diesel). For example, there are hardly any studies available that investigate (plug-in) hybrids alongside the simultaneous use of e-fuels.

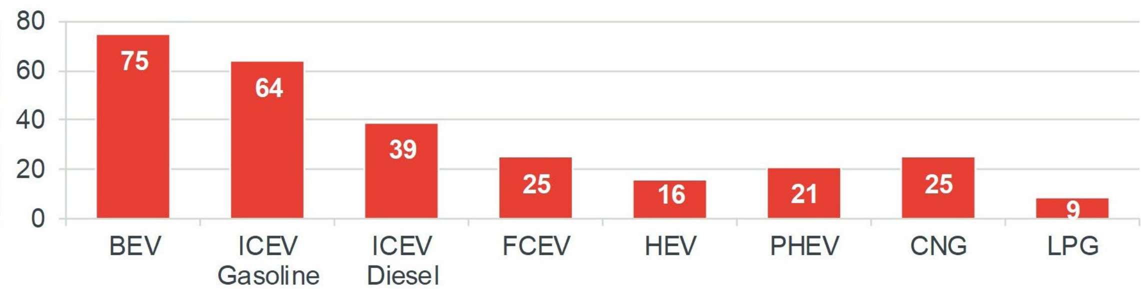

Figure 13: Some powertrains (leaving technological options aside) are only sparsely covered

Note: The chart shows the number of studies that analyse the respective powertrain technology. HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, CNG = compressed natural gas vehicle, LPG = liquefied petroleum gas vehicle.

Therefore, in addition to completeness, comparability in terms of specific analytical details is also a challenge. The number of different assumptions made for the respective key parameters (e.g. regarding the technological lifetime) underline the need for conversions and adjustments to compare the results of different studies and therefore even more numerous technologies.

In the following chapter, we take the most necessary steps to make the data comparable and inspect its completeness; both in general and for the single life-cycle sections.

7 E-fuels like e-diesel and e-gasoline generate tank-to-wheel emissions on a par with their fossil equivalent. However, during the fuel production (well-to-wheel) process, as much CO_2 is captured from the atmosphere (negative emissions) as is later emitted, which is why e-fuels emit net-zero emissions.

From a climate protection perspective, no single technology comes out on top

Available studies show a very heterogenous picture regarding overall CO_2 emissions arising from different alternative powertrain options in the traffic sector. The finding – which we will examine more closely in this chapter – is as follows:

- Regarding CO_2 emissions, there is no clear superior technology. Life-cycle analysis prove that CO_2 emissions are similar for many of the drive technologies available.
- However, emissions differ significantly between the different life-cycle sections of the different technologies.
- Consequently, the choice of the most advantageous technological option depends on individual assumptions and specific underlying conditions.

»Technologies tend to show similar emissions with no clearly superior alternative.«

A life-cycle comparison of the climate footprints of battery electric, combustion engine-driven and fuel cell vehicles shows relatively minor differences in many cases, which are strongly dependent on key assumptions – with none of the technologies being clearly superior in all cases.

Figure 14 summarises the study results on total CO_2 emissions of combustion engines (for both fossil and e-fuels), BEVs (both with an electricity mixture including fossil resources and green electricity) and FCEVs (both with hydrogen from fossil and renewable sources) over the entire vehicle lifetime. For this analysis, we use the results of all reviewed third-party studies and display their range and distribution:

- Each of the transparent bars in the background of the figure illustrates the median emissions for the respective life-cycle section.
- These bars are displayed following the logic of a waterfall diagramme and, when stacked, comprise the total CO_2 emissions of the vehicle. In other words, the upper end of the transparent:
  - blue bar shows the value of the median study's result for total vehicle emissions from the respective powertrain fuelled with fossil energies.
  - green bar illustrates the value of the median study's result for total emissions from a powertrain fuelled with renewable energy.
- The non-transparent boxes indicate how the results are distributed across the studies for each life-cycle section. These boxes illustrate the mid 50% of all study results for the respective life-cycle section. The range of the middle 50% of results is already wide, not least because of the varying assumptions and scenarios in the different studies. By "variation" we refer to the absolute distance between the upper and lower

bounds of the non-transparent boxes.
- The grey whiskers reaching out from the boxes, further extend the range across the entire bandwidth, from maximum to minimum results for the respective life-cycle section.

With comparability in mind, the results have been scaled to a similar life mileage of 150,000 km but otherwise left unchanged. Assumptions differ regarding vehicles (e.g. size or type/style), framework conditions (e.g. electricity mix or topography) and scenarios (e.g. purpose of use), meaning the studies are not completely comparable. Furthermore, the studies do not meet the requirements of a complete comprehensive analysis mentioned above. They often exclude CO_2 emission effects in other sectors – for instance, energy infrastructure is not analysed in detail in any of these studies.

Accordingly, although most of the study results still fail to constitute a complete comprehensive analysis and cannot thus provide a full picture, they already allow for some early findings in **Figure 14**:

- **No "winner" technology:** Depending on the respective study, different powertrain technologies show the lowest life-cycle emissions, but there is no single dominating technology. The stacked median total lifetime emissions for the three powertrains lie within the range of 25-35 t CO_2 using partly fossil energy, however, with considerable uncertainty (see below) and 9-16 t CO_2 using renewable energy.
- **High uncertainty:** However, the difference in results for individual technologies is huge across all studies, with differences between minimum and maximum results often far outstripping total median emissions. This is partly explainable by underlying scenario assumptions: Various traffic sector applications spawn numerous individual cases where different factors influence the total CO_2 balance. Some drivers such as the energy or electricity mix affect all life-cycle sections. Other drivers such as vehicle size, consumption and mileage are specific to some of the technology's life-cycle sections.
- **Vehicle production and the well-to-wheel phase (combination of fuel production and use phases) are the main emission drivers:** For vehicles running on fossil fuels or drive electricity mainly generated from fossil resources, the two phases of vehicle production and well-to-wheel cover most of the lifetime emissions in all powertrain technologies. Nevertheless, the picture changes when renewable energy sources are used as drive energy: In studies based on such "green" scenarios, emissions decline significantly during the vehicle well-to-wheel phase, leaving vehicle production as the main emission driver (note that only very few studies also consider the effect of increasingly renewable energy sources on the CO_2 footprint of vehicle's production – in a fully defossilised world, vehicle production is also likely to spawn close-to-zero emissions only, independent of powertrain technologies).
- **Infrastructure emissions often overlooked:** As **Figure 12** already shows, many studies fall short of analysing the emissions related to the build-up of the required (energy) infrastructure. A placeholder alone is thus included in **Figure 14** to visualise the existing information gap, but obviously all previously drawn conclusions are based on the caveat that the infrastructure has yet to be analysed in full.

Figure 14: Based on life-cycle analysis, different powertrain concepts show similar total emissions

Note: To ensure rough comparability, study results have been scaled based on a lifetime vehicle mileage of 150,000 km.

»Emissions occur at different life-cycle phases for different powertrain technologies.«

The comparison of various powertrains in **Figure 14** shows that despite relatively similar total life-cycle emissions for the various powertrains (considering the huge overlapping bandwidth of results), the way these emissions are distributed along the life cycle varies significantly across the different technologies:

- Emissions from vehicle manufacturing (red boxes in **Figure 14**) are comparably high for BEVs and FCEVs,
- Vehicle well-to-wheel emissions are:
  - Higher for ICEVs (the value of the median study's result is 23 t CO_2 per vehicle) and FCEVs (the value of the median study's result is 22 t CO_2 per vehicle – though these results are based on a very limited study base and particularly driven by assumptions on the hydrogen origin) than BEVs (the value of the median study's result is 15 t CO_2 per vehicle) when fossil fuels and a non-100% renewable electricity mix are used (dark blue boxes);
  - Generally far lower for all three technologies when these vehicles run on e-diesel (the value of the median study's result is 2.5 t CO_2 per vehicle), green H_2 (the value of the median study's result is 3.3 t CO_2 per vehicle) and almost-zero CO_2 electricity for charging (the value of the median study's result is 0.8 t CO_2 per vehicle), respectively[8];
- While the infrastructure sector has not been considered in studies on life-cycle analysis, differences between the single drive technologies would also be expected.
- End-of-life emissions also differ somewhat, but at a different order of magnitude overall compared to other life-cycle phases.

In the following section we discuss the main driver and results for each of the life-cycle phases in detail. The differences between the technologies adversely impact the effectiveness of narrowly focused climate policy measures and could result in significant distortions and disincentives, which we elaborate further at the end of this subchapter.

»Emissions from the manufacturing of vehicles are higher for BEVs and FCEVs than ICEVs.«

Figure 15 compares emissions from the life-cycle section "vehicle manufacturing" for ICEVs (gasoline- and diesel-powered), BEVs and FCEVs.

The one-off emissions from **ICEVs** manufacturing remain in similar dimensions for all the different studies analysed, with most differences attribut able to different car body sizes and difference in volume and origin for the required steel.

In comparison, one-off emissions from **BEVs** tend to be significantly higher than for ICEVs. This is because for the manufacturing of BEVs not only steel production emissions apply, but battery manufacturing also has a large impact. Manufacturing battery capacity is an energy-intensive process with a correspondingly high climate impact. Accordingly, the greater the required capacity and the more CO_2-intensive the electricity mix in the manufacturing country, the higher the resulting CO_2-footprint from only manufacturing the battery.

8 Theoretically, with all other things equal, well-to-wheel emissions should be equally low or even zero for e-fuels-run ICEVs or FCEVs and BEVs charged with 100% green electricity. In practice, not all else is equal and differences arise due to different underlying assumptions, such as the respective CO_2-intensity of the energy used to build up renewable energy facilities such as the wind parks used to produce the renewable charging current and renewable e-fuel.

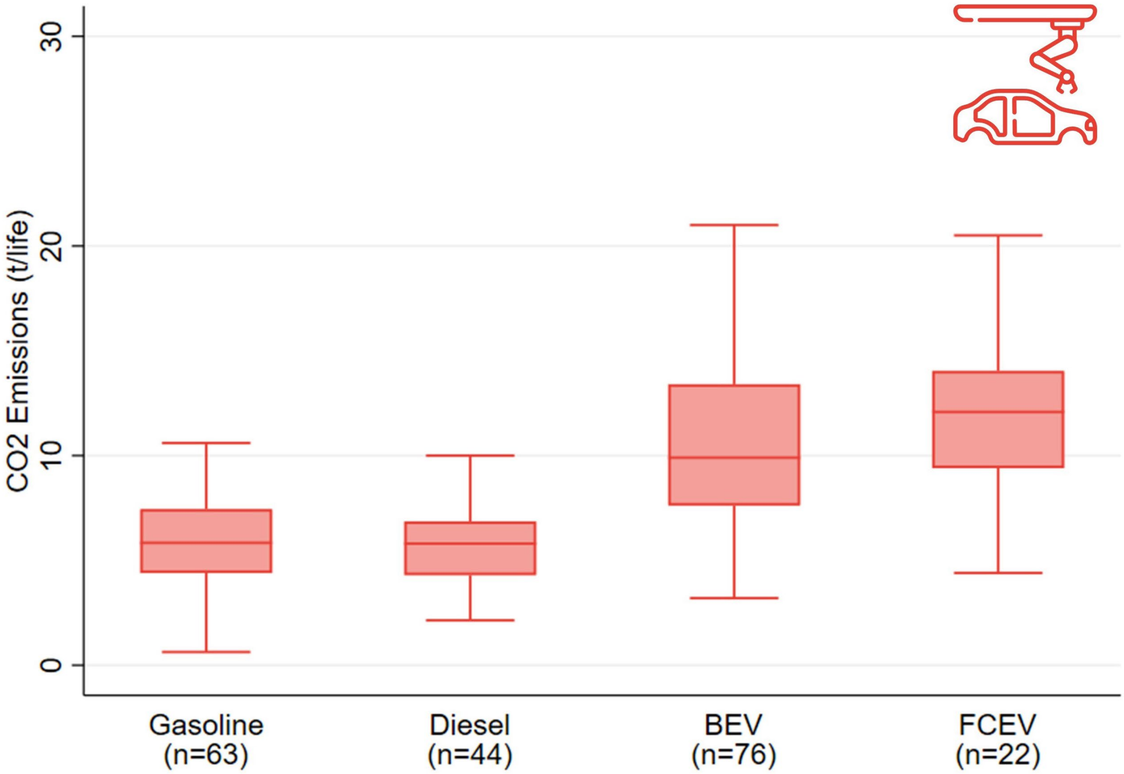

Figure 15: Battery and fuel cell production are central drivers for emissions from vehicle manufacturing

Note: CO_2 emissions are measured in tonnes per life.

Determining the **battery capacity** for a vehicle is a decisive parameter for total emissions but depends directly on the assumed use pattern. Consequently, with battery technology there is a new degree of freedom in configuring a vehicle, which is irrelevant for ICEVs and which makes it harder to compare single vehicles: For combustion engine vehicles, the vehicle range is solely determined by tank volume and therefore comes almost free (compared to other cost factors) and vehicles have generally been planned as "all-rounders" with a long range. However, with a BEV the vehicle's range (which determines the battery capacity) becomes one of the key cost drivers, meaning the planned range will be differentiated to a far greater extent for a BEV, depending on its application. Accordingly, life-cycle emissions (which are largely also driven by battery capacity) will differ significantly whether a BEV with low or high range is assumed, as opposed to remaining almost constant for an ICEV. With this in mind, the relativities between both powertrain technologies depend heavily on the assumed use cases (and the extent to which the vehicles are tailored to this specific use-case).

Similar findings apply to the **production site**: Currently, most batteries are produced in Asia, i.e. in China, Japan and South Korea, where battery manufacturing emits considerably more CO_2 due to the energy mix prevailing in those countries compared to Europe[9] (where different dimensions of sustainability also prevail).

9 See Chuang et al. (2018), p. 425, and EEA (2020), https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(current%20composition)%22%5D%7D%7D, accessed 07.01.2020

The median emissions for **FCEVs** manufacturing tend to lie even above BEV manufacturing. The main drivers for the high emission intensity of an FCEV in the study results are the energy-intensive production of the fuel cell and – to a lesser extent – the hydrogen tank. However, the informative value of the FCEV results is limited, firstly given a far lower sample size than for the other vehicles and secondly, the fact that the variation – and thus the uncertainty of results – peaks for FCEVs. The variation results from:

- The different electricity mix in the countries where fuel cells are produced: Most fuel cells are produced in Japan or in the USA, but also in European countries like France and Germany.
- Power differences in fuel cells: While the assumed hydrogen tank sizes in the studies do not vary significantly (by the equivalent of around 5 kg of hydrogen), the peak power of the fuel cells ranges from 46 kW[10] to more than 120 kW[11] and the greater the power, the higher the emission intensity.
- Non-standardised production processes: Fuel cells are still not a mass market, with few vehicle series on the market and the manufacturing processes yet to be fully commercialised.[12]

To **sum up**, emissions from vehicle manufacturing are higher for BEVs and FCEVs than ICEVs due to the additional effort involved in producing the battery or fuel cell. However, several issues complicate the comparison between technologies. One challenge is drawing a fair comparison between ICEVs, which serve as all-rounders for different uses and BEVs, which should serve more specific use requirements. Another challenge is finding comparable FCEVs and BEVs, since there are currently only middle and upper-class FCEVs.

»Emissions from fuel production and vehicle use (well-to-wheel) tend to be higher for ICEVs.«

Figure 16 compares the well-to-wheel emissions for gasoline and diesel-driven ICEVs, BEVs and FCEVs and shows that the studies tend to identify well-to-wheel emissions peaking for ICEVs based on fossil fuels. However, huge uncertainties remain, especially for FCEVs, as shown by the variation.

Emissions of a gasoline-powered **ICEV** exceed those one fuelled by diesel due to the higher efficiency of a diesel-driven ICEV. For both ICEV technologies the variation in total emissions originate from both:

- Well-to-tank emission variation: The well-to-tank emissions of ICEVs theoretically cover the production of gasoline or diesel, extending from fuel extraction and processing/refining to transport. However, different studies consider different parts of the upstream chain; and
- Tank-to-wheel emission variation: Vehicle consumption increases with size and weight of vehicles.

Most of the studies assume the exclusive use of fossil-based fuels for ICEVs. Nevertheless, a few studies also analyse the option of fuelling climate-neutral fuels, e.g. biofuels or synthetic varieties made from renewable energy sources. We separated these studies in **Figure 16** and the results show, that with climate-neutral fuels, well-to-wheel emissions in ICEVs are reduced by over 90%.

10 See Simons and Bauer (2015).
11 See Bauer et al. (2015).
12 See Evangelisti et al. (2017).

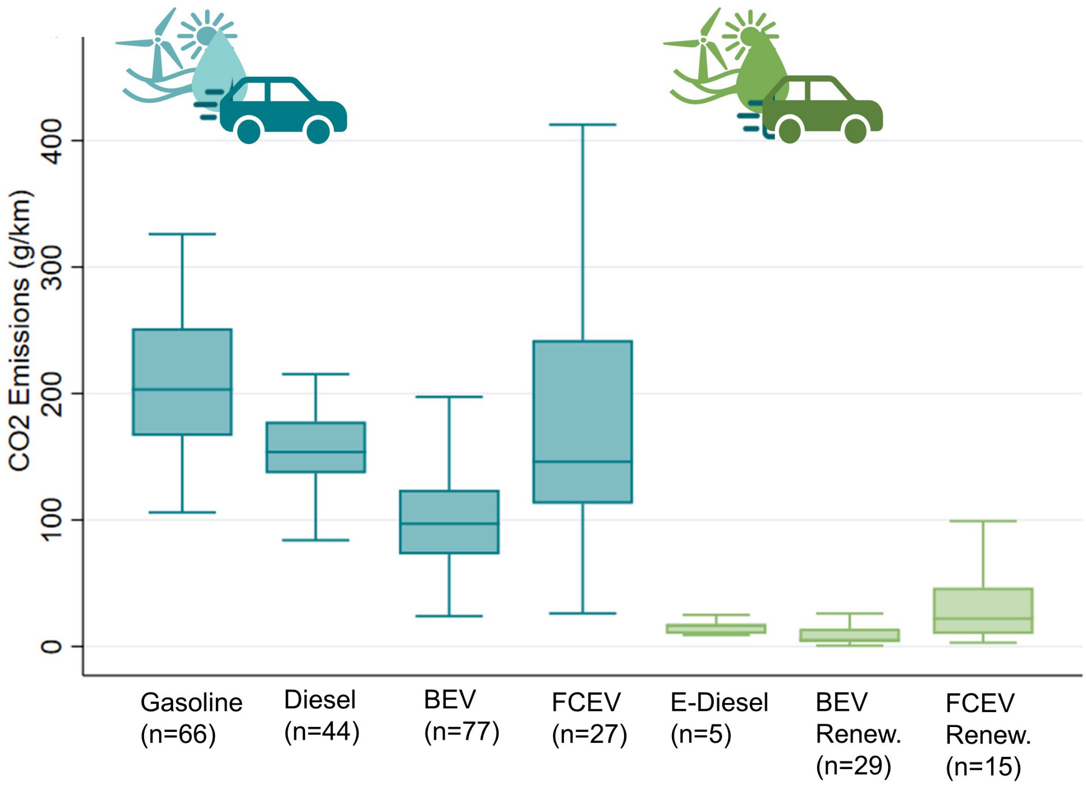

Figure 16: Electricity mix and consumption drive well-to-wheel emissions

Note: CO_2 emissions are measured in tonnes per life.

Well-to-wheel emissions of **BEVs** are – like ICEVs – driven by vehicle size and weight. However, emissions are purely well-to-tank[13] since BEVs are emission-free during the use phase and predominantly driven by the electricity mix used to charge the vehicle. Almost-zero well-to-wheel emissions for a BEV can only be reached with electricity generated from 100% renewable sources. Some studies already assume such a green electricity mix for charging, others consider the actual electricity mix in specific countries like Germany, France or the United States. Most studies do not consider that even green electricity for charging should include emissions from constructing renewable electricity generation plants. As shown in several meta-analyses of CO_2 emissions over the life cycle of RES plants – the impact is generally considerable and therefore relevant for life-cycle vehicle emissions using renewable electricity directly or indirectly (through conversion into e-fuels).[14] However, the total emissions are rather low compared to the life-cycle emissions of e.g. a coal-fired plant.[15]

Well-to-wheel emissions of FCEVs – like a BEV, a FCEV is emission-free during the use phase – tend to be lower than of ICEVs but exceed those of BEVs. However, the variation is striking and mainly attributable to the differing production methods for hydrogen with varying CO_2 intensities. Studies consider not only dif-

13 Usually, however, studies do not consider charging losses.

14 Life-cycle emissions for PV plants range from 1 to 300 g CO_2eq/kWh electricity, for wind onshore from 0.43 to 220 g CO_2eq/kWh and wind offshore from 3.2 to 29.7 g CO_2eq/kWh. See IPCC (2014), Nugent and Sovacool (2014), Amponsah et al. (2014), Kadiyala, Kom malapati and Huque (2017) and Kommalapati et al. (2017). For example, a medium value of 100 g CO_2eq/kWh would result in emissi ons of up to 13% of the total CO_2 emissions of a BEV.

15 A coal-fired plant produces 675-1689 g CO_2eq/kWh electricity over the lifetime. See IPCC (2014), p. 538.

ferent processes to produce hydrogen, i.e. separating hydrogen from natural gas via steam methane reforming – either using carbon capture and storage (often called “blue hydrogen”) or not (“grey hydrogen”) – or electrolysis (often referred to as “green hydrogen”). For hydrogen produced via electrolysis, studies also consider different electricity mixes and the resulting CO_2-intensity of the produced hydrogen varies accordingly.

Overall the variations in well-to-wheel emissions for all technologies show that present-day emissions vary according to the specific vehicle type and user behaviour involved. These differences are even reinforced by different regional circumstances such as the electricity or fuel mix. Going forward, the opposite trend can be expected: Since more and more drive energy is produced renewably, whatever technology is involved, differences between vehicle types and usage behaviour are set to decline and may even be eliminated. Emissions of BEVs can, for example, be avoided via electricity for charging that is increasingly green, while emissions for ICEVs and FCEVs can be avoided by blending in renewably produced e-fuels.

»Emissions from the provision of infrastructure occur for alternative technologies – especially electricity-based.«

As shown in Chapter Chapter 2 Motivation and Approach, as per section "Choosing technologies sustainably requires a comprehensive cross-sectoral, global and intertemporal life-cycle analysis", energy infrastructure is usually omitted from life-cycle analysis for vehicles. Accordingly, the common data used as a benchmark for our meta-analysis lacks depth on this topic, despite the fact that it has to be considered when assessing any meaningful technological choice.

The white spot/gap will be complicated to rectify, requiring extensive research. Indeed, several studies would potentially be required to specifically focus on infrastructure and assess emissions related to building energy infrastructure for the transport sector (e.g. filling and charging stations as well as energy grid extensions solely).

Although we cannot draw on robust data, in this section we nevertheless try to provide a rough "back-of-the-envelope" analysis in estimating the emissions involved. This analysis targets a rough mosaic, leveraging the results of multiple studies, each with its own very specific focus.[16]

Here, the magnitude may indeed be significant, namely – depending on the type of powertrain technology – between 0 and 2.8 t CO_2eq/car, thus constituting between 5 and 8% of overall emissions, which means it should be considered in life-cycle analysis. Depending on the powertrain technology considered, the number of elements and their respective importance differs as shown in **Figure 17**.

16 This means that a detailed comprehensive literature review for every element of energy infrastructure is not part of this study. We prioritise e.g. studies which are published more recently.

	ICEV fossil	ICEV e-fuels	BEV	FCEV grey H_2	FCEV green H_2
Pipelines for liquids	✓	✓			
Pipelines for gas				✓	✓
Trucks	✓	✓		✗	✗
Tankers	✓	✓		✓	✓
Electricity grid		✗	✗		✗
Storage for liquids	✓	✓			
Electricity storage			✗		
H2 storage				✓	✓
Stations	✓	✓		✗	✗
Charging stations			✗		

✓ Infrastructure available ✗ Infrastructure gap

Figure 17: Required infrastructure expansions depend on current infrastructure availability and gaps

Note: A certain amount of electricity storage will probably also be required for e-fuels and green H_2, but the level is expected to be far lower than for BEVs, so we exclude this aspect for ICEVs fuelled with e-fuels and FCEVs fuelled with green H_2 in the following.

For a large-scale roll-out of **BEVs**, additional infrastructure may be imperative, like charging stations, grid extensions or additional electricity storage facilities. The following rough estimations indicate that the CO_2 emissions caused by a BEV for the build-up of infrastructure may be of the order of magnitude of **up to 2 t CO_2/life** of a vehicle (see **Figure 18**), i.e. **up to 7.3%** of the total CO_2 emissions of a BEV.

- Estimates based on selected studies for emissions for constructing and operating **charging stations** range from **0.06** (lower case) **to 0.45 t CO_2eq** (upper case) over the lifetime of a BEV. The large range is driven by, on the one hand, different types of charging stations (AC private, AC public, DC public) and on the other, different estimates for the forecast total of charging stations required per BEV[17].
- The expansion of the **electricity network** due to a roll-out of BEVs will likely generate further CO_2 emissions[18]. Based on several studies and further assumptions, we estimate emissions between **0.02 kg CO_2eq** (best case for transmission networks) up **to 0.48 t CO_2eq** (value for distribution networks) may be expected based on BEV lifetime electricity consumptions[19]. Finally, it is important to note that the values given above might underestimate the actual emissions occurring du-

17 Lucas, Silva and Neto (2012), Bünger et al. (2019) and Robinius et al. (2018).

18 A meta-analysis of studies on the network impact of charging infrastructure by FGH from 2018 (FGH 2018) concluded that only a few studies quantify network extension and since these focus on selected model grids only, generalisation is difficult. A year later, Navigant, Kompetenzzentrum Elektromobilität and RE-xpertise (2019) estimated a huge range of required network expansion in Germany depending on the selected scenario.

19 These values are derived from studies, which analyse CO_2 emissions over the life cycle of electricity lines and typically indicate CO_2 emissions per transported MWh electricity (Jorge and Hertwich (2013), Arvesen et al. (2015), Harrison et al. (2010), Turconi et al. (2014) and Madrigal and Spalding-Fecher (2010)). Since we assume that 50% of the electricity grid is already available, we reduce the values for CO_2 emissions per MWh by 50%. However, the actual value of emissions will depend largely on the number of BEVs, assumed charging patterns and whether the charging is controlled or uncontrolled. See e.g. Navigant, Kompetenzzentrum Elektromobilität and RE-xpertise (2019) and FGH (2018).

ring the front-loaded construction of the lines since the CO_2 emissions are depreciated in studies over the electricity lines' lifetime of 40 to 100 years[20].

- **Electricity storage** is required to ensure the electricity supply (especially from intermittent renewable energy sources) and demand is temporally aligned – over either the short or long term. Due to additional electricity demand for BEVs, systemwide storage demand is also likely to increase. Emissions for electricity storages, built because of additional electricity storage demand for BEVs, can be assumed to range **from 0 to more than 1 t CO_2eq/BEV**, depending on assumed CO_2 emissions per storage technology[21] and the storage required[22].

FCEVs require the construction of hydrogen filling stations, a (bigger) fleet of trucks for transporting H_2 to the filling stations and – for green hydrogen – potential expansion of the electricity grid. Other types of infrastructure are available but need to be technically adjusted to ensure H_2 compatibility, e.g. gas pipelines, tanker[23] and storage. In total, we get a spread of **0.91 to 2.82 t CO_2/life** of an FCEV running with green hydrogen (shown in **Figure 18**), which comprises up to 7.8% of total CO_2 emissions of a FCEV.

- The CO_2 emissions of **hydrogen filling stations** are estimated by Wulf and Kaltschmitt (2018) and **also include the transport and the preparation for transport**. In Germany, they refer to 1.21 kg and 2.46 kg CO_2/kg H_2 as the minimum and maximum values respectively. Assuming a consumption of 1,260 kg H_2/life for a medium-sized car[24] and a 40% provision of already existing infrastructure in the best case and 20% in the worst case, we can estimate a range of **0.91 - 2.48 t CO_2/life** for infrastructure emissions for an FCEV running with grey hydrogen.
- Regarding the case of green hydrogen, the **electricity grid** may require an expansion depending on the location of the conversion plants, i.e. whether the plants are located closely to the renewable energy sources. In the first case, the related CO_2 emissions can be assumed to be close to zero. For the latter case, we estimate additional grid-related emissions of **0.34 t CO_2eq/life**[25].

Finally, it is reasonable to assume that the infrastructure for an **ICEV run by fossil fuels** already exists, which means **no additional emissions**[26]. Contrary, for an **ICEV run by e-fuels**, the electricity grid may require – similarly to an FCEV running with green H_2 – an expansion depending on where the conversion plant is located. In a situation where

20 Most of the studies refer to a lifetime of 40 years, Jorge and Hertwich (2013), even to 100 years.

21 CO_2 emissions from constructing and operating storage differ depending on the type of storage and – according to Mostert et al. (2018) – range from 9 kg CO_2eq per stored MWh(el) for second-life batteries to 176 kg CO_2eq per stored MWh(el) for sodium-sulphur batteries. Denholm and Kulcinski (2003) cite higher values for single batteries, but this might be due to technological development and the values remain within the range given above. If we then assume that only 25% of new storage capacity needs to be built since BEVs themselves also provide some storage capacity, emissions range from 2.25 to 44 kg CO_2eq/MWh for BEVs in this category.

22 The amount of electricity needing to be stored for a BEV ranges from 0 to 24 MWh. For this, we initially assume total consumption of 33.6 MWh of electricity over the lifetime (based on 150,000 km mileage lifetime and a consumption of 0.224 kWh/km – including charging losses and electricity for climatisation and electronic services). Second, we assume that in a more optimistic case 0% of this electricity needs to be previously stored (0 MWh(el)) and in a more pessimistic case 70% (24 MWH(el)).

23 Transport via tanker can take place via hydrogenation and dehydrogenation with a liquid organic hydrogen carrier. If dibenzyltoluene is chosen, the handling during transport is the same as for a conventional mineral oil-based fuel. See Wulf and Kaltschmitt (2018), p. 6.

24 This value is based on consumption of 0.0084 kgH_2/km for a Hyundai Nexo (see e.g. https://www.hyundai.de/modelle/nexo/, accessed 17/01/2020) and a life mileage of 150,000 km.

25 This presupposes efficiency of the electrolysers of 70% (see Frontier Economics 2018, p. 64), a consumption of 1,260 kgH_2/life (see footnote 24) and that compared to a BEV only 40% of the grid infrastructure need be added. In addition, we discount the CO_2 emissions per MWh by 50% – similar to the case of a BEV.

26 It may, however, be necessary to replace investments, but as with other technologies we abstract from any needs for re-investments in existing infrastructure.

power to liquid plants are located close to the renewable energy sources, no additional electricity network expansion might be required, so no additional grid-related emissions would be generated. The same is true if e-fuels were fully imported via pre-existing infrastructure for liquids. As a likely **maximum value** of grid-related CO_2 emissions, we estimate **0.43 t CO_2/life**[27], shown in **Figure 18, i.e. 4.7%** of total CO_2 emissions for an ICEV run by e-fuels.

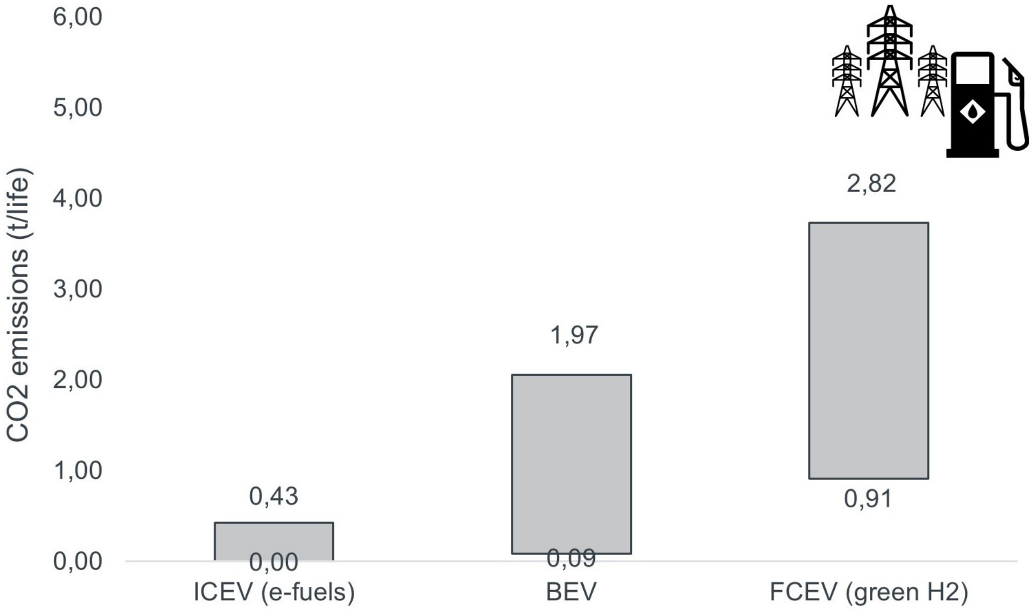

Figure 18: Infrastructure emissions are hardly analysed but potentially relevant

As the quoted literature shows, these very rough calculations are based in each case on only one or a few sources, which raises **major questions over their robustness.** The emissions from the provision of infrastructure are therefore an area that requires further research. This is even more important as the "back-of-the-envelope" calculations above suggest – namely that the share of CO_2 emissions resulting from energy infrastructure remains not insignificant and should not be ignored.

27 To calculate this value, we first assume a power-to-liquid conversion efficiency of 55% as the above assumed efficiency of 70% of an electrolyser combined with an efficiency of 79.9% for the conversion of hydrogen to a liquid fuel (see Fashihi and Breyer (2017)) results in an efficiency for total conversion from electricity to a liquid fuel of ca. 55%. Second, compared to the BEV case, where the electricity grid needs to cover the whole distance between production and consumption site, we assume that the grid only needs to cover for 20% of the distance – also due to higher import levels of e-fuels. This value is lower than those for a FCEV run by green H_2 since it assumed that due to the lower efficiency of a power-to-liquid unit (compared to a pure electrolyser) the levelled cost of electricity are more important and e-fuels are therefore more likely to be imported. Finally, we discount again the CO_2 emissions per MWh by 50%.

»The extent of emissions from end-of-life remains uncertain.«

The level of emissions that occur after driving a vehicle, i.e. during the recycling or scrapping process, remains uncertain. Only few studies cover end-of-life emissions, particularly on FCEVs.

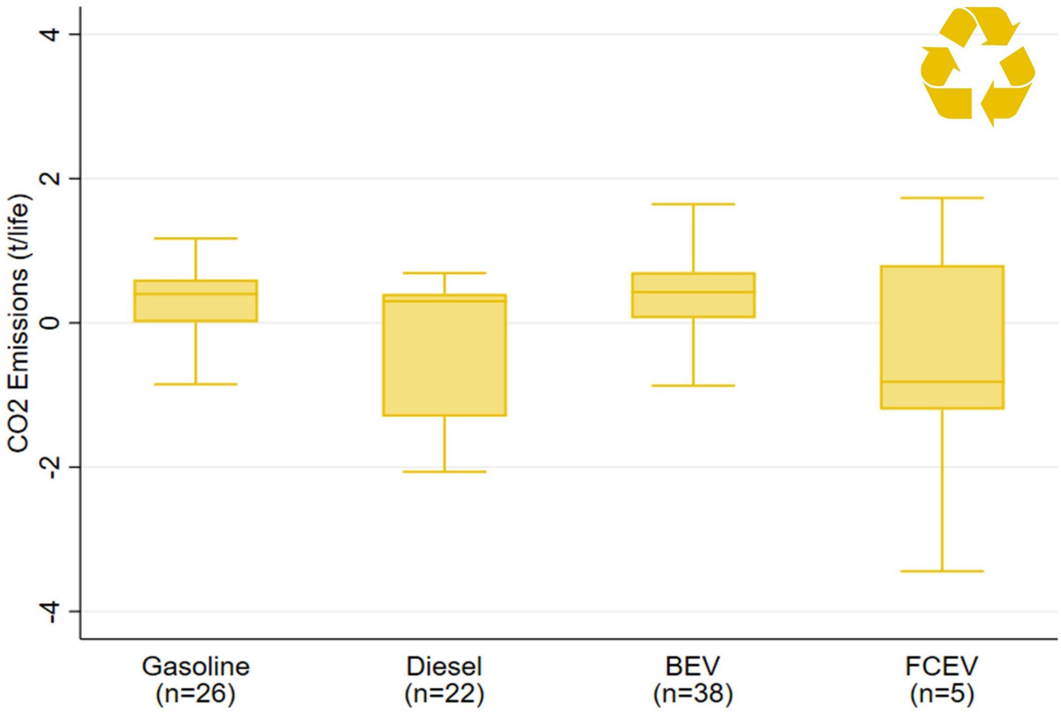

Figure 19: High uncertainty on main drivers for end-of-life emissions

Note: CO_2 emissions are measured in tonnes per life.

Despite the uncertainty, two major results can be derived from **Figure 19**:

- Firstly, end-of-life emissions are low compared to emissions at the other stages of the life cycle. We estimate medians between -0.82 and 0.43 t CO_2eq/life. Some studies even state negative emissions, especially for diesel-fuelled ICEVs, BEVs and FCEVs. The reason is that negative emissions might occur when recycling and further using the vehicle components for other application cases is feasible, replacing CO_2-intense raw materials. Batteries could potentially serve as stationary short-term storage, e.g. in buildings ("2nd life"). However, lack of experience and empirical data on batteries means high uncertainty. Also, for the argument on negative emissions, the assumed counterfactual (e.g. using new rather than recycled batteries) would require further scrutiny.
- Secondly, the end-of-life emissions tend to be quite similar in size across vehicle technologies – except for FCEVs, where insufficient data impedes any sound conclusions.

»Implication: Narrowly focused policy measures might distort an otherwise well-balanced technological choice.«

The above detailed review of the studies' findings on emissions across various life-cycle phases showed significant differences between technologies on where the bulk of emissions occur, despite our earlier finding that overall emissions – considering the wide bandwidth of study results – are quite comparable across technologies.

This has important implication for the policy design, as we have already pointed out in Chapter 2: If climate policy measures focus only on specific parts of the life cycle (as e.g. the fleet targets focus only on tank-to-wheel emissions), technologies which happen to be emission-light in this specific life-cycle phase become relatively more advantageous, even though this might be compensated by simply "moving" large parts of the emissions elsewhere. Accordingly, the findings in this Chapter on the significant differences between technologies strengthen the case for a comprehensive, life-cycle based policy approach rather than the sector-specific views which currently prevail.

»The overall CO_2 emission balance strongly depends on the individual case and specific underlying conditions.«

Another key conclusion of our meta-analysis is that the advantages of different powertrain technologies are strongly dependent on specific application and underlying conditions assumed in the various studies. We already pointed to several key drivers in this regard, e.g.

- Where and how vehicle parts are produced (because e.g. the production power-mix has a huge impact),
- Circumstances of vehicle usage, such as driving patterns, range requirements, required charging/fuelling time, etc.
- Assumptions on energy sources (renewable vs. fossil) and infrastructure (existing or to-be-built),
- And not least the remaining uncertainty affecting many of the parameters.

This has important implications regarding the applicability of life-cycle analysis: Even with an improved data basis life-cycle analysis will only be able to support technological choices within a restricted framework. Given the multitude of possible vehicle applications and circumstances, it is highly doubtful, **that a centralised technology decision will ever be able** to consider the full breadth of parameters and constraints which actually drive the results of any meaningful CO_2 emissions along the life-cycle analysis. We discuss possible policy implications in the following chapter.

From a technological perspective, all powertrain technologies can achieve a CO_2-neutral mobility!

However, even in situations where comparing technology based on a life-cycle analysis might be useful, defining similar assumptions for all technologies under review has to allow for a **"fair" comparison**:

Total emissions of BEVs, for example, can be reduced with increasingly renewable charging current. Simultaneously, additional renewable energy potentials pave the way to produce CO_2-neutral fuels (e-fuels). Accordingly, in an environment with increasing volumes of renewable energy, an increasing blend-in share of e-fuels should equally be assumed when analysing combustion engines (potentially alongside hybridisation).

To make the results more valid and reliable, further research is required to improve the robustness of parameters, decrease uncertainty and not least to fill the gaps identified (e.g. regarding energy infrastructure or recycling).

Technology-open and target-oriented approaches in climate policy ensure effective savings in CO_2 emissions

The key findings of our meta-analysis to date:

- Any climate policy decision targeted at individual technologies needs must consider a comprehensive cross-sectoral, global and intertemporal life-cycle analysis as a prerequisite to technologies being sustainably chosen.
- Unfortunately such a comprehensive database remains pending.
- What is already available indicates the lack of any clearly superior technology but the relative advantages of powertrain technologies depend instead on very individual circumstances.

Nevertheless, climate policy needs to address the challenges now. Accordingly, in this section, we outline which policy recommendations can be formulated already based on these findings.

»Incomplete information demands a target-oriented and technology-neutral policy approach.«

The summarised findings of our meta-analysis pose a fundamental dilemma for any present-day policy-making. A central decision-maker will hardly ever have enough information to identify the optimal technology for a universal use-case, because

- Today key information is still missing and a comprehensive database is unlikely to be available anytime soon; but more importantly
- Many parameters depend on the individual use-case and are therefore unsuitable by nature for central decision-making; and not least because
- We must assume that for many technologies, the future configuration of mobility behaviour and further underlying conditions will change over time. Accordingly, today many forthcoming developments remain unpredictable.

Hence, any technology-specific decision today bears a significant risk to be proven wrong in future. Accordingly, the major recommendation to policy makers is to avoid micro-managing individual technological choices as much as possible. Political instruments should be designed to be technologically neutral and market forces should be leveraged to develop efficient mixes of technologies for CO_2-savings – especially with individual mobility requirements and unsafe future developments in mind.

In this respect, technological openness means that as well as all technologies available today, potential future developments and innovation can also help save emissions and compete on a level playing field. Policy incentives should therefore focus on the overarching objective, i.e. CO_2 reductions, as well as allowing individual stakeholders to make unbiased and decentral decisions.

Based on the findings in this study, it is thereby important to ensure incentives for CO_2 abatement are part of a comprehensive approach and consider emissions

- intertemporally,
- across all sectors,
- on an international scale.

In light of these recommendations, today's climate policy measures in Germany and Europe in the mobility sector have to be critically questioned: Present-day policy measures are overly technology-specific, with a strong sectoral focus and lacking efficiency. E.g. the incentives to reduce emissions on the well-to-wheel path are split between well-to-tank and tank-to-wheel. Fuel providers are acting in response to the upcoming RED II regulation, which falls under well-to-tank. Conversely however, OEMs are the only stakeholders incentivised to reduce emissions within the tank-to-wheel section, namely through fleet targets. Regulating the two life-cycle sections separately spawns numerous inefficiencies; for example, market players are currently forced to reduce emissions within the limited boundaries of the respective section, while widening the scope of well-to-wheel regulation would enable a more flexible approach to determine how and where emission reductions are the most cost-efficient. Equally questionable are technology-specific programmes and objectives, such as individual targets for electric vehicles.

In the context of our meta-analysis results, these policy measures should be critically reviewed and improved as part of a more comprehensive technology-neutral approach.

»One-off vehicle emissions in combination with a long lifetime require special consideration of the temporal dimension.«

Another policy recommendation is directly derived from the findings:

- That the climate effect – and therefore the Paris Agreement – follows the logic of the **budget principle**, which implies that the stock of cumulated emissions is relevant (rather than the flow of annual emissions, see **Chapter 2** Motivation and Approach); and

- That o**ne-off emissions** from vehicle manufacturing constitute a **significant** share of total vehicle lifetime emissions (see **Chapter 3** Results).

So in combination, it becomes clear that the fixed budget of allowed emissions could be accidentally used up early due to significant one-off emissions if policy measures result in over-hasty replacement of the existing fleet. Instead the two mentioned findings trigger the important dynamic implication – namely that the timing of policy measures is crucial and the quicker the policy implementation the better does not always apply.

The budget principle of climate relevant emissions implies that sooner policy implementation is not always better.

To achieve the climate protection targets efficiently, there will instead be a need to leverage all available options to abate CO_2 emissions and consider the options' respective overall net effect on emission savings. This requires accounting for all emissions, irrespective of the sector, region or point in time at which they occur. This implies (despite being often neglected) that one-off emissions arising in the industry sector should also be considered, as an even greater priority, given that they tend to be high.

- By focusing on single-sector targets – especially those of the road transport sector and thus emissions linked to vehicle use – it might appear beneficial to exchange the fleet as quickly as possible. Given the focus of fleet targets on tailpipe emissions, one conclusion might be to increasingly use measures that incentivise swift vehicle fleet replacement while other potential CO_2 saving measures for the existing fleet remain unexplored.
- However: One-off emissions of vehicle manufacturing irrevocably influence the remaining CO_2 budget. To meet the climate target of a maximum global temperature increase of 1.5 or 2°C, respectively, only a certain quantity of greenhouse gas may be emitted. The IPCC estimates the remaining budget to range between 420 to 580 Gt CO_2eq if the 1.5°C-target is met with a probability of 50 to 66%[28]. Consequently, CO_2 emissions require a cumulative analysis, irrespective of when they are generated.

Due to the budget principle, bulk one-off emissions caused by a hasty exchange of the vehicle fleet could easily use up a large share of the existing budget. Accordingly, an over-hasty technology switch might hinder efforts to lower cumulated CO_2 emissions over time: Due to high one-off emissions, which are in a similar order of magnitude to total emissions during the vehicle use phase, exchanging the fleet prematurely might even lead to the emission budget being exploited prematurely.

Figure 20 illustrates this, based on a rough estimate for the Federal Government transport sector target by 2030:

- The Federal Government's aim of reducing CO_2 emissions in the transport sector by 40% by 2030 corresponds to around 400 million (m) t of CO_2eq from 2018 to 2030, assuming a linear path[29]. Assuming approx. 60% of CO_2 emissions in the German traffic sector are caused by cars, this elicits a cumulative saving target for cars of approx. 240 m t of CO_2eq by 2030.
- This amount of CO_2 is roughly similar to what is emitted by all 47 m cars in the German fleet today[30]. In other words: If it were theoretically possible to double the service life of today's cars and thus skip a single generation of vehicles without any other changes to mobility patterns or fuels, similar net savings would emerge.
- Or contrarily: If policy measures envisaged to reduce emissions trigger a premature (partial) exchange of the fleet, this could easily offset a significant proportion of the net savings.

Accordingly, for additional CO_2 emissions, it might be sensible to exchange the existing fleet more slowly rather than promote an over-hasty technological exchange. Conversely, at some point the savings achieved by new and more efficient vehicles justify replacing the existing fleet, despite the additional one-off emissions generated by new vehicles. An efficient climate policy should therefore ensure that a technology exchange follows an intertemporally optimal path, e.g. coordinated with the usual reinvestment cycle.

28 See IPCC (2018), p. 14.

29 The 400 m t CO_2eq result from multiplying the difference of total emissions between 2030 (aim to reduce them down to 95 m t CO_2eq) and 2018 (actual emissions of 162 m t CO_2eq) with 12 years and dividing them by two.

30 See Kraftfahrt-Bundesamt, https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/bestand_node.html, accessed 11/10/2019.

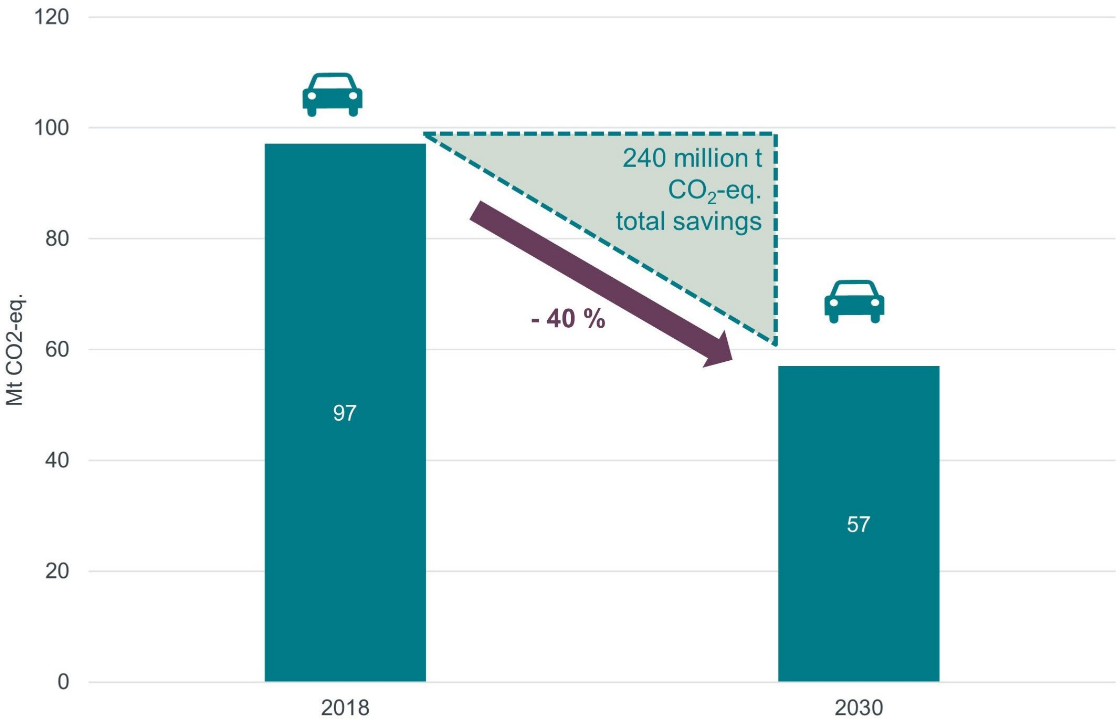

Figure 20: There is only a very limited CO_2 budget left for the transport sector if 2030 intermediate targets are to be met

»Sectoral targets incentivise emission shifts instead of emission reductions.«

Climate policy measures are often limited to a specific sector, e.g. the EU fleet targets focus on emissions during on-road use of vehicles and thereby on the transport sector. In contrast, emissions in the energy and industry sector, that are also generated from vehicle manufacturing or fuel production, are not addressed by a transport-specific measure but left to other sectors to handle. Accordingly, such a sector-specific view often fails to help the emissions problem in the most efficient manner overall, but instead merely relies on shifting emissions to other sectors.

We illustrate this with a simple exemplary calculation for the political target of introducing up to 10.5 m BEVs by 2030 in Germany[31]:

The German government's objective set in the Climate Package[32] is to have between 7 m and 10 m BEVs on the streets by 2030. This objective is mainly built on NPM AG 1 (2019), p. 21, which estimates that replacing 10.5 m ICEVs by BEVs by 2030 (which would be 6.5 m more electric vehicles than in the reference scenario) would reduce emissions by 13 m t CO_2[33] per year by 2030 relative to the reference scenario. This may be a reasonable estimate for emissions directly attributable to vehicles, i.e. tailpi-

31 BMU (2019), p. 6.

32 Bundesregierung (2019), p. 76.

33 NPM AG 1 (2019), p. 21. The 13 m t CO_2 emission saving is the delta between a 6.5 m ICEV fleet and a 6.5 m BEV fleet.

pe/tank-to-wheel. However, if we widen the perspective and also consider other sectors and cumulative effects based on our meta-analysis findings, it becomes obvious, that this policy measure would elicit a far lower reduction in global emissions.

Figure 21 shows that most of the emission reduction shown for the transport sector constitutes not a genuine reduction in emissions but often only a shift of emissions to other sectors. Accordingly, by 2030 **only 6%** of the emission reductions attributed to transport sector will have really been achieved while most emissions have moved into other sectors or geographies, with uncertain effects on total emission reductions:

- We start our back-of-the-envelope calculation with the NPM AG 1's estimation **of 13 m t CO_2 emissions savings in the** tank-to-wheel life-cycle stage in 2030.[34] We then widen the annual perspective to a cumulative perspective: 13 m t CO_2 emissions for the specific year 2030 correspond to **65 m t CO_2** cumulated emissions[35] from 2020 by 2030 tank-to-wheel. This assumes a linear substitution of the additional 6.5 m ICEVs by BEVs between 2020 and 2030.[36]
- We then examine the remaining stages of the life cycle – i.e. other than tank-to-wheel – and estimate the respective impacts on emissions of launching 6.5 m BEVs based on our findings in the meta-analysis:
  - A further **8.8 m t CO_2** emission savings from the well-to-tank phase of ICEVs: By 2030, 8.8 m t CO_2 will be saved at the fuel production stage in the global energy sector due to eliminating the need to produce gasoline or diesel for ICEVs.[37]
  - However, in the well-to-tank phase of battery electric vehicles, additional cumulative emissions of **51.5 m t CO_2** are pushed into the energy sector since the German electricity mix will not be carbon-free by 2030.[38]
  - There will also be additional emissions from infrastructure expansions: As indicated in Chapter 4 we lack a robust database of infrastructure-related emissions. We use our indicative estimate (see Chapter 4) and quantify additional infrastructure emissions at approx. **3.6 m t CO_2** by 2030. This estimate has to be regarded as conservative since we assume a "depreciation" of emissions over 40 to 100 years of the infrastructure lifetime. However, factually, the emissions occur during the build-up of the infrastructure, which means in practice that they will be front-loaded, increasing the emission impact in the period up to 2030.[39]

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34 The numbers given below are based on the following assumptions: Yearly mileage: 16,000 km, mileage over lifetime: 150,000 km, yearly well-to-tank emissions of a BEV: 1.58 t CO_2 - derived from a consumption of 22.4 kWh/100km (compact car WLTP plus 10% losses for charging and climate regulation) and a CO_2 intensity of the electricity mix 2026 of 437g/kWh (incl. 42g/kWh REN-E plants, International Energy Agency forecast 2018).

35 Alternatively, we could express emission savings in g CO_2/km rather than in m t CO_2. This is illustrated by the values in the left column of Figure 21. I.e. for the tank-to-wheel phase, the annual 13 m t CO_2emission savings correspond to reduced emissions of 124 g CO_2/km.

36 As many of the reviewed studies only specify well-to-wheel rather than well-to-tank and tank-to-wheel emissions, our meta-study result is also expressed in overall well-to-wheel values. For the analysis here, therefore, we have to assume a plausible split between the life cycle phases in line with the meta-analysis results presented in Chapter 4. Yearly tank-to-wheel emissions are assumed to be 0 t CO_2 (BEV) and 2 t CO_2 (ICEV, based on a consumption of 5.6 l/100km, compact passenger car, WLTP). Accordingly, 6.5 m BEVs (linearly replacing ICEVs between 2021 and 2030) save 65 m t CO_2.

37 We assume yearly well-to-tank emissions of 0.27 t CO_2 (ICEV, based on a consumption of 5.6 l/100km, compact car, WLTP).

38 The estimate is based on the International Energy Agency forecast for the average emission intensity of the German power mix in 2026 (incl. rucksack) of 437g/kWh. While the overall emissions in the power sector are capped by the EU ETS, to assess the full emission effect of marginal changes to electricity consumptions it is also important to consider crowding-out effects (e.g. moving demand outside the EU ETS).

39 We assume life-cycle infrastructure emissions of 1.03 t CO_2 (BEV) and 0 t CO_2 (ICEV fuelled with diesel).

– Finally, additional emissions of **14.8 m t CO_2** in the industrial sector might occur from producing and recycling BEVs compared to ICEVs.[40] Again, the value is rather conservative, since it is only a pro-rata share assuming a mileage over the lifetime of 150,000 km[41]. In addition, the risk of premature replacement of the 6.5 m fleet is not considered.[42]

Based on these calculations on life-cycle impacts, an additional switch to 6.5 m BEVs by 2030 might immediately only deliver an accumulated net reduction in 3.9 m t CO_2, about 6% of the stated 65 m t CO_2 reductions in the transport sector. The vast share of what are presumably reduced emissions is instead shifted into other sectors or geographies, whereupon the net impact on emissions is far less clear.

Overall, this simple example shows the importance of a life-cycle view for all policy measures to deliver effective, global climate protection.

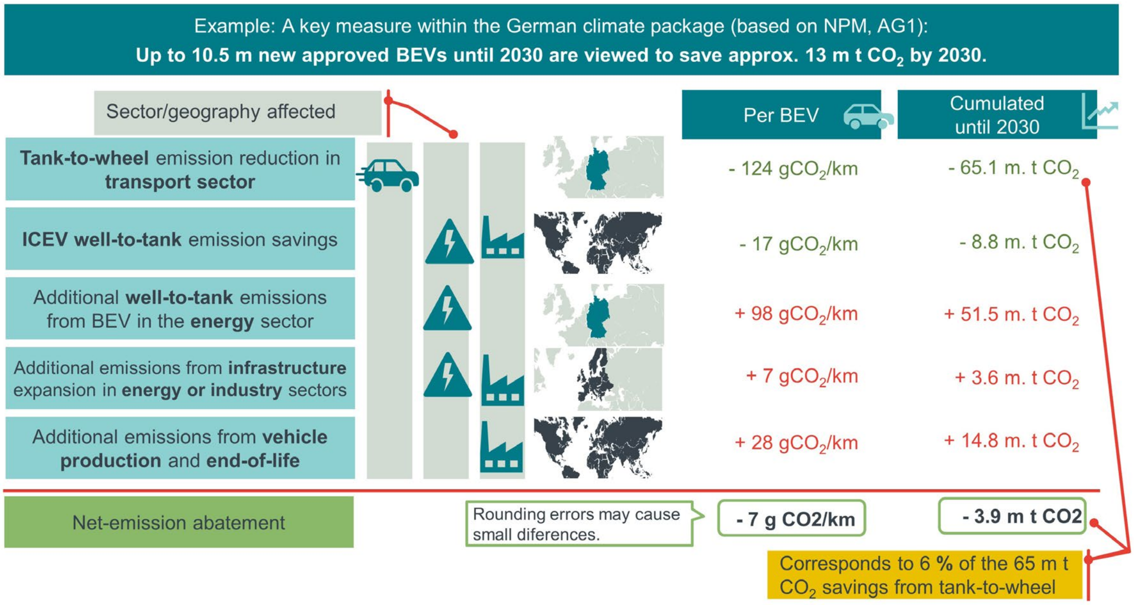

Figure 21: German target to reduce transport emissions by introducing up to 10.5 m BEVs mainly leads to a shift of emissions into energy and industrial sectors

Note: Sectors affected: Car icon = transport sector, arrow in triangle icon = energy sector, factory icon = industrial sector. Cumulated values are based on a linear market introduction of additional 6.5 m BEVs, i.e. each year from 2021 onwards 0.65 m BEVs substitute ICEVs and in 2030 all additional 6.5 m BEVs are on the market.

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40 We assume manufacturing emissions of 9.90 t CO_2 (BEV) and 5.80 t CO_2 (ICEV) and end-of-life emissions of 0.43 t CO_2 (BEV) and 0.30 t CO_2 (ICEV), whereby we assume that an equal part is attributed to each year of the vehicle lifetime. Since – with a linear market launch of BEVs between 2021 and 2030 – the average BEV starts driving in 2026 and we measure the accumulated emissions at the end of 2030, our calculation includes the first 5 years of the average vehicles' life-time manufacturing and end-of-life emissions, which reflects a pro-rata share of 53% (16.00km * 5years / 150.000 km lifetime mileage).

41 Instead, if we used the total emissions rather than the pro-rata share from producing 6.5 m BEVs instead of 6.5 m ICEVs, the emissions would amount to 27.5 m t CO_2.

42 If we assumed that, e.g. due to policy incentives, car owners replaced their ICEVs before their actual end-of-life by BEVs, the bulk of one-off emissions would increase even more due to this "extraordinary depreciation".

»In conclusion, we need to see the bigger picture and embrace technology.«

Our analysis illustrates the importance of a comprehensive – namely, cross-sectoral, global and intertemporal – approach for achieving the climate target of 1.5 or 2°C of global warming.

- A **cross-sectoral approach** is important to minimise the total emissions across all sectors instead of just shifting them from one sector to another and even risking an increase in total emissions.
- A **global** approach is essential, since where emissions occur is irrelevant for the greenhouse effect.
- An **intertemporal approach** means that any emissions, regardless of when emitted, must not be ignored because – due to the budget principle – only a certain amount of greenhouse gases can be further emitted worldwide to achieve the climate target.

This should be reflected in climate policies, which require a bird's eye approach: Policies need to be cross-sectoral rather than sector-specific, global rather than national and need to take all steps of the value chain into account (i.e. also the emissions from vehicle manufacturing and drive energy production).

Furthermore, we can conclude that although many studies and analyses are already available, important information for a comprehensive life-cycle assessment is still missing, e.g. for the life-cycle phase "infrastructure" and relevant powertrain technologies (e.g. FCEVs or e-fuel-run powertrain technologies). Also, a CO_2 emission balance strongly depends on the individual case and the specific underlying assumptions.

As a positive finding, we determined that there is no clear superior or inferior technology but instead that all available technological options can deliver mobility on comparable CO_2 emission levels, with a long-term perspective of virtually carbon-neutral mobility. This paves the way for technological choices, which should ideally be incentivised by a technology-neutral policy approach, allowing each end-user to trade-off the advantages and downsides of the respective powertrains in the context of the specific use-case – without compromising on climate protection contributions.

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List of figures

A briefing paper summarises the most important results of the study:
›Efficient use of the global CO_2 budget in the mobility sector– Four theories based on a meta-study on life-cycle analyses‹

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Climate protection in the mobility sector needs a sustainable approach.

This is the conclusion from a new meta-analysis on cradle-to-grave life-cycle assessments on alternative powertrain technologies jointly performed by FVV and Frontier Economics. In order to make a good choice among available technological alternatives, it is essential to provide policy makers, industry and consumers with robust and reliable data material. For this new analysis more than 80 studies from the last 15 years have been identified and reviewed that examine the life-cycle CO_2 impact of vehicles and powertrains. From a climate perspective, no single technology came out on top. Zero-impact emissions and climate neutrality by 2050 require a technology-open, cross-sectoral, global and intertemporal approach.

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