Carbon Budget Compliance: A life-cycle-based model for carbon emissions of automotive Original Equipment Manufacturers

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Abstract

Automotive Original Equipment Manufacturers (OEMs) cause considerable amounts of CO_2 emissions over the life cycle of their vehicles. They are thus contributing to global climate change. To stop climate change, all industries, including OEMs, must accomplish a major reduction of CO_2 emissions. OEMs report past emissions and receive external support for setting Paris Agreement-compatible reduction targets. Though currently, OEMs do not have access to a methodology that facilitates modelling their future absolute emissions and the leverage of reduction measures at the company level. They are thus unable to develop holistic carbon reduction strategies. Here I demonstrate that current carbon management approaches remain conceptual. Based on the analysis of OEMs' future emission drivers, requirements are developed to evaluate additional methods for their applicability in the subsequent method derivation. Quantifying the effect of integrating mobility services in OEMs' fleets on the company's absolute emissions is evaluated as especially important. For this reason, the Carbon Budget Compliance (CBC) method is developed by integrating and refining the analysed approaches. This method facilitates computing the impact of single reduction measures on fleet level over the life cycle of vehicles and mobility services regarding compliance with a carbon budget.

The CBC method is exemplarily applied in a case study for the Volkswagen Group (VW). In scenario analyses the leverage of using renewable energy sources for battery production and electrified vehicles' use phase is computed for fleets consisting of private vehicles and mobility services (car sharing, ride hailing, ride pooling). VW's absolute emissions between 2015 and 2050 are modelled regarding the compliance with a 2 °C-compatible carbon budget. I show that immediate operationalisation of the two reduction measures for private vehicle and mobility service fleets is crucial for budget compliance. Due to higher load factors, ride hailing and pooling vehicles provide more person-km (p-km) during their lifetime than private vehicles. Fleet sizes in these scenarios are thus reduced. As heavier ride pooling vehicles need higher battery capacities than average Group vehicles, ensuring the use of renewable energy sources over their life cycle is crucial to attain absolute emission reduction. Otherwise, the reductive effect of smaller fleets is counterbalanced. The load factor of car sharing vehicles is similar or equal to private vehicles. By offering car sharing, OEMs can thus only reduce absolute emissions via an earlier onset of fleet electrification and the use of renewable energy sources. The high dependence on the energy sector's decarbonisation efforts calls for OEMs to play an active role in the provision of sufficient amounts of renewable energy. The lowest modelled overshoot of the carbon budget is 5% facilitated by a combination of ride hailing and private vehicles as well as by operationalising the reduction measures.

OEMs should therefore analyse additional measures tackling the supply chain and less CO_2-intensive emission categories such as logistics within the CBC method. The method facilitates modelling such measures due to its modular approach. By using the CBC method, OEMs are now able to develop effective carbon reduction strategies to support achieving global climate targets and monitor their success. To improve the CBC method, future research should address the automation of data flows between data systems and the integration of micro-scale mobility models to quantify rebound effects caused by mobility services. Coupling internal carbon pricing with the CBC method could further promote its applicability in OEMs' daily business operations.

Zusammenfassung

Automobilhersteller (OEMs) verursachen den Ausstoß erheblicher Mengen an CO_2-Emissionen über den Lebenszyklus ihrer Fahrzeuge und tragen somit zum globalen Klimawandel bei. Um den Klimawandel zu stoppen, müssen jedoch alle Industriesektoren, einschließlich der OEMs, CO_2-Emissionen massiv senken. OEMs veröffentlichen ihre Emissionen bereits jährlich und können Reduktionsziele berechnen, die mit den Anforderungen des Pariser Abkommens übereinstimmen. Es existiert jedoch bislang keine Methode, mit der zukünftige absolute Emissionen modelliert und Reduktionsmaßnahmen auf Unternehmensebene ganzheitlich bewertet werden können. Verfügbare CO_2-Management-Ansätze sind rein konzeptionell und zeigen praktische Anwendungen nur unzureichend auf. Demgegenüber werden hier basierend auf der Analyse zukünftiger Emissionstreiber von OEMs Kriterien entwickelt, um weitere Ansätze hinsichtlich ihrer Verwendbarkeit für die Methodenentwicklung zu bewerten. Insbesondere die Quantifizierung des Effekts von Mobilitätsdienstleistungen in den Flotten der OEMs auf deren absolute CO_2-Emissionen wird hierbei als wesentlich erachtet. Dazu wird die Carbon Budget Compliance (CBC) Methode mithilfe einer Kombination verschiedener Ansätze entwickelt. Die CBC Methode ermöglicht die Berechnung des Hebels von einzelnen Reduktionsmaßnahmen auf Flottenebene über den Lebenszyklus von Privat- und Service-Fahrzeugen hinsichtlich der Einhaltung eines OEM-spezifischen CO_2-Budgets. Die CBC Methode wird exemplarisch in einer Fallstudie auf die Volkswagen AG (VW) angewendet, in der die absoluten Konzernemissionen von 2015 bis 2050 hinsichtlich der Einhaltung eines 2 °C-kompatiblen CO_2-Budgets modelliert werden. In Szenarioanalysen wird der Effekt zweier Reduktionsmaßnahmen berechnet: Die Nutzung erneuerbarer Energiequellen für die Batterieproduktion und für die Nutzungsphase elektrifizierter Fahrzeuge. Die betrachteten Flotten bestehen sowohl aus Privat- als auch aus Service-Fahrzeugen (Car Sharing, Ride Hailing, Ride Pooling). Die Auswertung der Szenarien zeigt, dass die sofortige Umsetzung der Reduktionsmaßnahmen notwendig ist, um die Einhaltung des CO_2-Budgets zu ermöglichen. Wegen höherer Besetzungsgrade stellen Ride-Hailing- und Ride-Pooling-Fahrzeuge mehr Personen-km (p-km) über ihre Nutzungsdauer bereit als Privat-Fahrzeuge, sodass die Flottengröße in diesen Szenarien reduziert wird. Da die durchschnittlich schwereren Ride-Pooling-Fahrzeuge jedoch höhere Batteriekapazitäten als privat genutzte Fahrzeuge benötigen, ist die Nutzung erneuerbarer Energiequellen über den gesamten Lebenszyklus notwendig, um eine absolute Emissionsreduktion zu erreichen. Andernfalls wird die durch die kleinere Flotte erreichte Emissionsreduktion wieder ausgeglichen. Der Besetzungsgrad von Car-Sharing-Fahrzeugen ist denen privater Fahrzeuge ähnlich oder gleich. OEMs, die Car Sharing anbieten, können daher ihre absoluten Emissionen nur durch eine frühere Elektrifizierung der Flotte und die Nutzung erneuerbarer Energiequellen reduzieren, nicht aber über die Flottengröße. Durch die Flottenelektrifizierung sind OEMs auf die Dekarbonisierung des Energiesektors angewiesen. Um absolute Reduktionsziele erreichen zu können, sollten OEMs aktiv daran arbeiten die Verfügbarkeit ausreichender Mengen erneuerbarer Energien sicherzustellen. In keinem der Szenarien wird die Einhaltung des CO_2-Budgets erreicht. Die niedrigste modellierte Überschreitung des Budgets beläuft sich auf 5% und wird mithilfe einer Kombination von Ride-Hailing- und Privat-Fahrzeugen sowie mit der Umsetzung der Reduktionsmaßnahmen erreicht. OEMs sollten daher weitere Maßnahmen in den Lieferketten sowie den weniger CO_2-intensiven Emissionskategorien wie Logistik mit der CBC Methode bewerten. Durch den modularen Ansatz der Methode ist die Modellierung verschiedenster Maßnahmen möglich.

Durch die Anwendung der CBC Methode können OEMs nun effektive CO_2-Reduktionsstrategien zur Erreichung globaler Klimaziele entwickeln und deren Fortschritt überprüfen. Zukünftige Studien sollten die Automatisierung von Datenflüssen zwischen Datensystemen sowie die Integration von Mikro-Mobilitätsmodellen in die CBC Methode zur Quantifizierung von möglichen Rebound-Effekten durch Mobilitätsdienstleistungen adressieren. Zusätzlich könnte die CBC Methode mit einem internen CO_2-Bepreisungssystem verbunden werden, um Maßnahmen nicht nur hinsichtlich ihrer Emissionsreduktion sondern auch ihrer Finanzierbarkeit bewerten zu können.

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1 Introduction

Anthropogenic carbon1 emissions are causing global climate change with predicted adverse effects for life on Earth. For this reason, the international community of states ratified the 2015 Paris Agreement which aims to reducing global carbon emissions to limit global warming to a maximum of 2 °C by 2100. In accordance with this global 2 °C target, Rogelj et al. (2016) estimated a remaining global budget of 590-1,240 Gt CO2 to be emitted between 2015 and 2050. The absolute reduction of carbon emissions is thus an urgent matter of public concern. Corporate carbon reduction efforts are crucial to attain global climate targets (Krabbe et al., 2015).

The transport sector contributes to 20% of global carbon emissions (IEA, 2014a). With predicted increasing mobility demand of over +150% between 2015 and 2050 in non-OECD countries (OECD/ITF, 2017), automotive Original Equipment Manufacturers (OEMs) are under pressure to find measures to cut carbon emissions while increasing their fleet sizes. Not only are tailpipe emission regulations tightening globally (ICCT, 2017) but stakeholders are increasingly demanding climate mitigation efforts over the life cycle of products and services (Busch and Schwarzkopf, 2013). Of the ten most vehicle-selling OEMs, 90% publicly reported absolute CO_2 emissions caused over the life cycle of vehicles sold worldwide in 2017 (CDP, 2018a; Forbes, 2017). Emissions reported to the not-for-profit organisation Carbon Disclosure Project (CDP) by the three top-selling OEMs – VW Group, Toyota and Renault Nissan – increased during the past four years (CDP, 2018a).

Though OEMs regularly publish Life Cycle Assessment (LCA) studies showing an increasing life-cycle carbon efficiency of new vehicles compared to preceding models (e.g. BMW, 2018a; Toyota, 2018; VW, 2015), these efforts are not yet sufficient for lowering absolute emissions. Accordingly, Bjørn and Hauschild (2013) state that increasing the carbon efficiency of products without an absolute emissions reduction target does not support the development of long-term strategies as the increasing consumption of products is not taken into account. The $I=PAT$ equation describes this phenomenon and shows the need for absolute carbon emission targets. Environmental impacts (I) depend on the development of population size (P), material affluence per capita (i.e. material wealth per capita) (A) and eco-efficiency (defined as material affluence per environmental impacts, $1/T$) (Bjørn and Hauschild, 2013). Although T is increasing due to technological advances such as carbon-efficient fuels, an increasing population seeking material affluence is likely to purchase an amount of produce outweighing the increase in carbon-efficiency achieved per product. Consequently, I is increasing although T is increasing as well. Therefore, absolute carbon reduction targets are necessary to ensure that not only is carbon efficiency increased but that overall carbon emissions are reduced (Doda et al., 2016).

A Paris Agreement-compatible absolute carbon reduction target for OEMs and for other sectors is determined by meeting the global 2 °C target as a minimum. Approaches breaking down this abstract target into specific carbon reduction pathways for sectors and single companies are available. OEMs like Daimler, Honda, Nissan, PSA Peugeot Citroen, Renault and Toyota already publicly committed their companies to achieving absolute carbon reduction targets in line with the requirements of the global 2 °C target based on one of the available externally verified approaches (SBTi, 2018a). However, as Liesen et al. (2013) and Marland et al. (2015) point out, the challenge is not to set a corporate environmental goal but rather to achieve it.

The prerequisite for any company aiming for a targeted reduction in emissions is knowledge of sources and amount of past emissions, i.e. corporate carbon accounting (Damert et al., 2017). On this basis, decisions on how to reduce corporate emissions in the future can be supported (Günther and Stechemesser, 2010) and corporate reduction strategies operationalized (Marland et al., 2015). As stated above, most OEMs already fulfil this requirement by reporting annual absolute carbon emissions

[1] The terms carbon/CO_2/GHG emissions are used interchangeably throughout this study. They refer to the GHG listed under the Kyoto Protocol: CO_2, N_2O, CH_4, SF_6, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) (WBCSD and WRI, 2004).

caused over the life cycle of sold vehicles. However, long-term strategic decisions regarding the 2050 timeframe of the Paris Agreement cannot solely be based on past carbon performance but need additional modelling of future carbon emissions to evaluate reduction measures (Schaltegger and Csutora, 2012). This is especially the case when an industry is offering complex products and is facing unprecedented changes.

OEMs are confronted with profound technological changes as well as a changing business environment. In the wake of growing demand for carbon-efficient vehicles alternative powertrains and fuels are being developed and gradually introduced to the market. Higher shares of electrified vehicles in their fleets help OEMs not to exceed tailpipe emissions regulations thus avoiding fines. However, with current electricity mixes, Battery Electric Vehicles (BEV) shift the CO_2 burden from tank-to-wheel (TTW) to well-to-tank (WTT) emissions and supply chains (Helms et al., 2016). Therefore, a shift from combustion engines to electric vehicles alone might not lead to absolute CO_2 reductions necessary to achieve a corporate and, consequently, a global 2 °C target. Hence, evaluating life cycle carbon emissions of passenger vehicles on fleet levels is crucial for OEMs to support decision-making on measures to effectively reduce their absolute emissions. This includes decisions on fleet composition, of powertrains in certain markets, vehicle sizes and the roll-out of carbon reduction measures from vehicle to fleet level.

Another development that is expected to transform OEMs' business models is the ongoing trend of servitization in the industry (see e.g. Correa (2018)). The shift of customer preferences from owning private vehicles to using mobility services is likely to impact not only the amount of cars sold but also OEMs' business model and consequently their absolute carbon emissions. Consulting firms have identified mobility services to be a disruptive trend for OEMs as the underlying business model inherently changes (Geissler et al., 2015; Heineke et al., 2017). Recently, OEMs started investing in and offering mobility services (Firnkorn and Shaheen, 2016). OEMs are thus transitioning from being solely a vehicle provider to becoming a vehicle and mobility provider. With estimated increased kilometrages of shared vehicles on overall vehicle kilometrage in Europe from less than 1% in 2017 to approximately 35% in 2030, it is crucial for OEMs to be able to estimate the impact of selling mobility services instead of vehicles on their absolute CO_2 emissions (PwC, 2018). Nonetheless, no long-term measurement nor predictions of OEMs' CO_2 emissions by including mobility services in their portfolio exist (Firnkorn and Shaheen, 2016) which leads to the subsequent problem situation of this dissertation.

1.1 Problem situation

OEMs have systems in place to quantify past CO_2 emissions. In addition, OEMs have approaches readily available to indicate their future levels of carbon emissions compliant with Paris Agreement requirements. For the development of a long-term carbon reduction strategy, though, modelling future absolute emissions is a prerequisite. However, approaches to model future emissions of companies and to evaluate reduction measures are lacking (Burritt et al., 2011). As Zvezdov and Schaltegger put it: corporate carbon management is "highly topical, yet under-researched" (2015, p. 27). Future absolute carbon emissions of OEMs will be influenced by numerous external and internal parameters as emissions arising during production, use and end-of-life phases ("from cradle to grave") of vehicles and mobility services are included.

A method for OEMs to model their future absolute carbon emissions is lacking. Currently, OEM managers are likely to decide on planned fleet compositions based on tailpipe emissions legislation in the respective markets. Managers cannot, however, judge planned fleets based on CO_2 emissions caused over the whole life cycle of to-be-sold vehicles. Reported past emissions show whether the company increased or decreased emissions compared to previous years only in retrospect. Facilitating OEMs' active role in planning future fleet compositions from a life cycle perspective of CO_2 emissions is thus crucial. Taking the scope and approaches used for past emissions accounting as a starting point, creating a method to compute future absolute emission scenarios is necessary. A life-cycle perspective on future emissions ensures the same scope covered by past reported emissions in addition to opening up possibilities to model the impact of CO_2 reduction measures in life-cycle stages not yet legally bound to CO_2 emission legislation, such as the supply chain or recycling. Computing future emissions until 2050 is more complex than calculating past emissions of a single year. In each market covered, tailpipe emission legislation, demand for amounts and types of vehicles are developing differently. Moreover, modelling the impact of offering mobility services (instead of private vehicles) on future absolute emissions is decisive as these are expected to change OEMs' business models in the near future.

Therefore, existing past-oriented carbon accounting approaches of OEMs need to be enabled to compute future absolute emissions to decide on fleet compositions and reduction measures directed at both vehicles and mobility services in order to comply with a Paris Agreement-compatible carbon budget until 2050. This problem situation leads to the following research objective.

1.2 Research objective

Based on the identified general research gap in 1.1, the first objective of this dissertation is to analyse the fundamental research fields addressing the enhancement of current carbon accounting systems in order to model OEMs' future absolute emissions in relation to a carbon budget. A concluding deficit analysis aims at delineating the research gap further. Subsequently, requirements for the to-be-developed method are set up addressing both methodological and practical requirements to be fulfilled. As such, both scientific accuracy as well as applicability of the method by an OEM is established. The concluding step shows the development of the Carbon Budget Compliance (CBC) method based on the insights of the deficit analysis and the elaborated requirements.

The resulting **main research question** is:

How can existing carbon management approaches of OEMs be enabled to model future absolute emissions at the company level in order to comply with a carbon budget?

The scope of carbon emissions in the research objective is shown in Figure 1. In order to answer the main research question, global CO_2 emissions of an OEM from a starting point in the past, e.g. 2015, until 2050 need to be analysed. These emissions are caused over the whole life cycle of OEMs' current and future fleets which consist of Light-Duty Vehicles (LDVs) and mobility services alike.

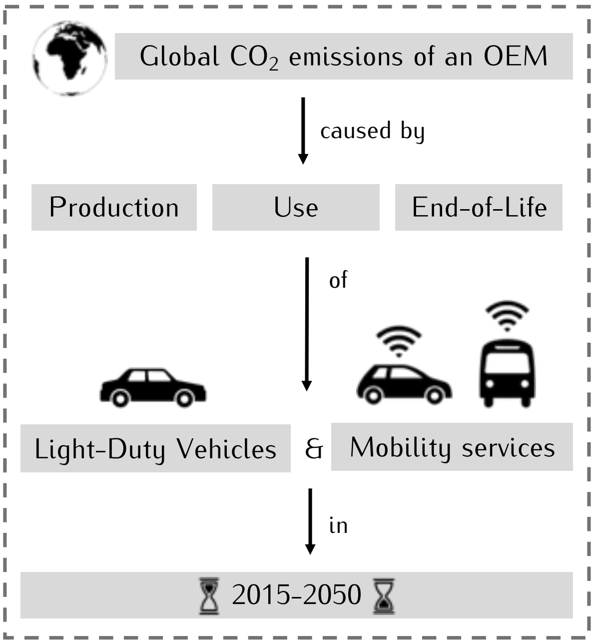


Figure 1 Scope of the research objective.

1.3 Methodological approach

In this section, the methodological approach to address the problem situation is explained. The different steps necessary to achieve the research objective are demonstrated and the main research question is broken down into sub-research questions. As such, the different work packages are explained. Finally, a workflow diagram visualises the pursued methodological approach.

The method of LCA provides the basis for this research project. Therefore, in the first step of this dissertation, the state of current academic knowledge on LCA in general and the comparison of private and mobility service vehicles' life cycle carbon performances in specific are evaluated. Building up on this, existing carbon management approaches of OEMs are described. The first sub-research question is, therefore:

Sub-research question 1
What are existing carbon management approaches of OEMs?

Next, in order to assess existing approaches' ability to model future absolute emissions, OEMs' future emission drivers are analysed. The resulting second sub-research question is:

Sub-research question 2
Which factors influence future absolute emissions of OEMs?

A following deficit analysis of the described approaches in combination with OEMs' future emissions drivers addresses shortcomings preventing the achievement of the research objective with the current state of academic knowledge. Based on these findings, methodological as well as practical requirements for the CBC method are established. Subsequently, these requirements are used to evaluate additional approaches found suitable to address the research gap. The third sub-research question is:

Sub-research question 3
Which requirements does the method need to meet in order to represent a high degree of scientific quality as well as practical applicability?

The integration of these requirements in one coherent modelling method represents the concluding method derivation. The corresponding sub-research question is:

Sub-research question 4
How can practical and methodological requirements be integrated in one modelling method?

As the CBC method needs to prove its applicability within an existing company, a scenario-based case study is performed to test its ability to evaluate the effect of different reduction measures on carbon emissions at the company level as well as the introduction of mobility services regarding the compliance with a Paris Agreement-compatible target like a 2 °C target, by 2050. The fifth sub-research question is, therefore:

Sub-research question 5
Does the method application demonstrate its applicability to evaluate carbon reduction measures over the life cycle of vehicles and mobility services regarding the compliance with a 2 °C-compatible carbon budget of an OEM?

In the final discussion and conclusion, answers to the combined five sub-research questions are evaluated. Final remarks on the main research questions are addressed in the conclusion. Workflow and structure of this dissertation and the location of research questions by chapters is depicted in Figure 2.

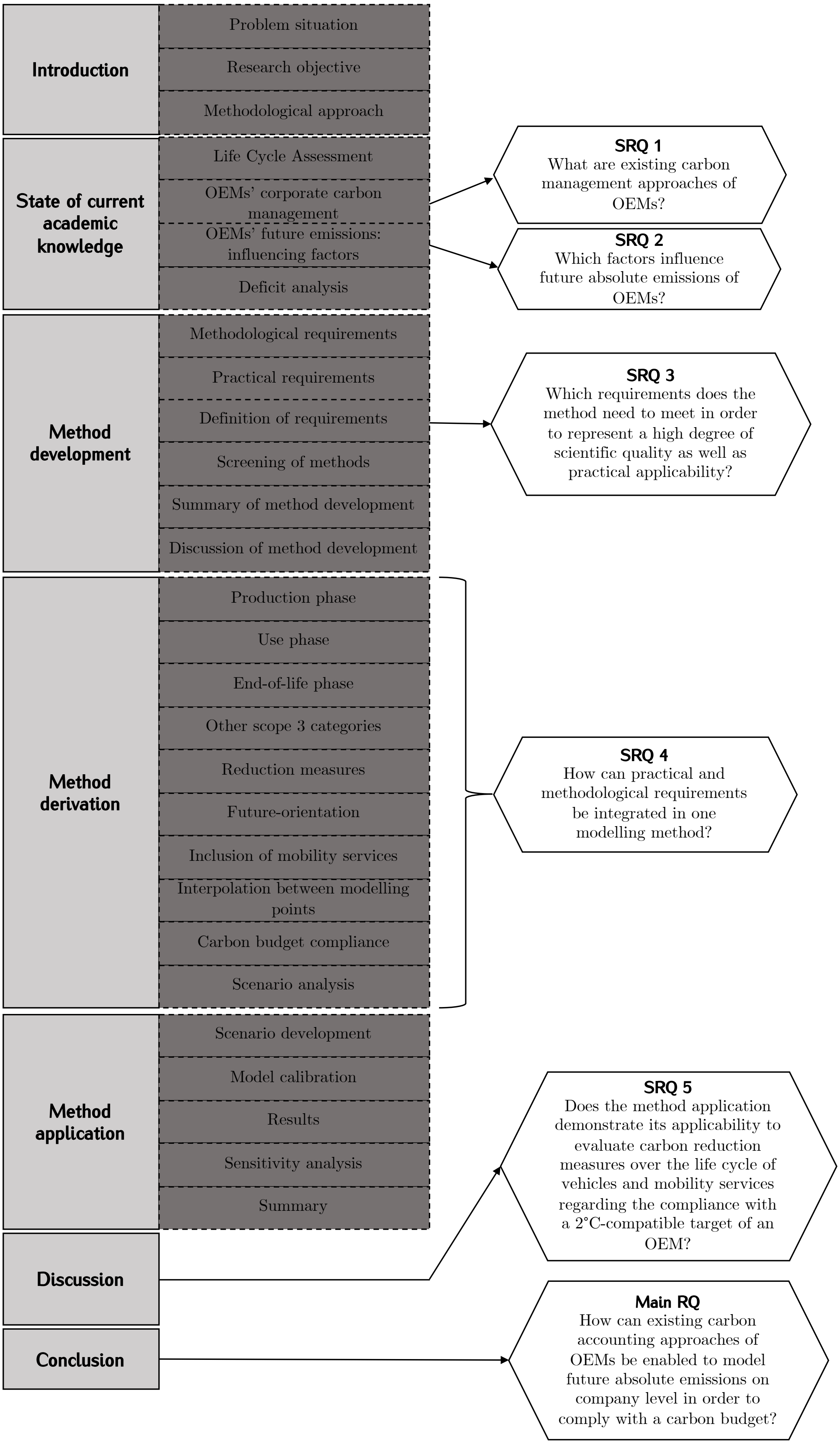


Figure 2 Workflow and structure of this dissertation including addressed research questions (RQ= research question, SRQ = sub-research question).

2 State of current academic knowledge

This chapter provides an introduction to current approaches corresponding with the thematic focus of this dissertation. In the first subchapter, the method of LCA is introduced being the main method used for assessing the environmental performance of products and services (Kjaer et al., 2016). In the following, the research field of corporate carbon management is described and assessed for approaches aimed at projecting OEMs' emissions and evaluating carbon reduction measures on a corporate level. Next, approaches for setting corporate carbon reduction targets in line with the Paris Agreement are introduced. Subsequently, factors influencing OEMs' future emissions are analysed to determine which parameters need to be included in the CBC method. Finally, a standardised literature review is performed regarding the LCA method's ability to compare life cycle carbon performances of private vehicles and mobility service vehicles. A shortened version of this part was published in Neef et al. (2019). The chapter is concluded with a deficit analysis which further delineates the research gap.

2.1 Life Cycle Assessment

The method of LCA is used to assess the environmental performance of any product which includes goods and services. The necessary procedures to perform an LCA are defined by the 2006 ISO Standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b). In an LCA study, consumed resources, emissions as well as impacts on the environment and human health are accounted for by calculating inputs and outputs throughout a product's complete life cycle. Within this cradle-to-grave approach, the manufacturing, use and end-of-life (EoL) phases are considered by calculating the resources extracted, the energy consumed and the emissions produced during each phase. The LCA assessment framework (Figure 3) includes four steps: (1) Goal and Scope Definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA), (4) Interpretation.

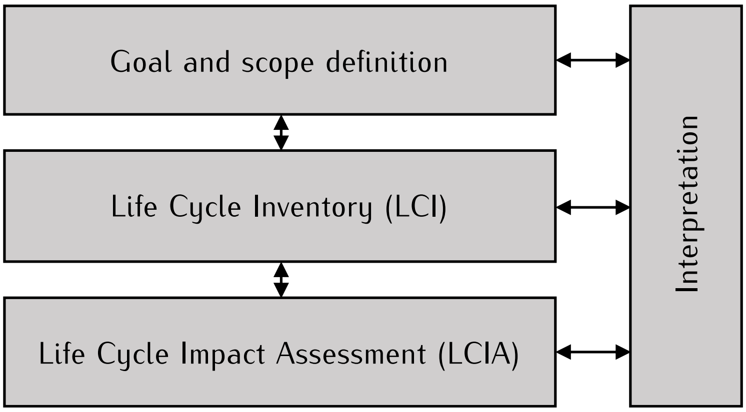


Figure 3 Iterative LCA approach according to Baumann and Tillman (2004).

The Goal and Scope (1) definition includes the description of the assessed product's function and the respective functional unit. For example, the function of a passenger vehicle is to transport passengers; the according functional unit could thus be n person-kilometres (p-km). In comparison, a truck's function is to transport goods so that the respective function unit could be n tonne-kilometres (t-km). The scope definition also includes the description of the system boundaries, i.e., whether all life cycle phases are included in the analysis and what processes are cut-off (EC-JRC, 2010).

In the LCI Phase (2), the data required by the goal and scope definition is collected and modelled. The relevant processes are identified and input and output flows are gathered. These include elementary flows such as resource consumption and emissions, product flows that connect the processes, and waste flows (EC-JRC, 2010). The data is either collected from databanks, available literature, manufacturers, or is estimated.

The third phase of an LCA is the Life Cycle Impact Assessment (LCIA). The potential environmental impacts of the exchanges of elementary flows collected in the LCI are converted into impact indicator results. According to the ISO standards, the obligatory steps in the LCIA are impact category definition, classification and characterization. The optional steps include normalization and weighting procedures (EC-JRC, 2010). In the following, the LCIA steps are explained by the example of the ReCiPe 2008 method which covers the obligatory steps described above (Goedkoop et al., 2009). The impact categories defined in ReCiPe are shown in Figure 4 ("Environmental Mechanism part 1"). In the following classification step, LCI results are assigned to an impact category. Environmental loads might also be assigned to several impact categories if the effects are independent of each other, e.g., NO_x which adds to eutrophication and acidification (Baumann and Tillman, 2004). In the characterisation, the contributions of the LCI results to the impact categories are quantified via equivalency or characterisation factors. For example, the impact category "Terrestrial Acidification" sums up the contributions of (among others) NO_x, SO_2 and HCl emissions. In case the LCIA result for a certain category is a positive value, it represents a damage to the environment. In case the value is negative, an impact is avoided because of, for example, substitution processes. It can therefore be seen as a benefit to the environment (ibid.).

The midpoint level is problem-oriented which means that impacts at one point of the environmental cause-effect chain are assessed. Units like kg CO_2 eq. are used to describe the impact on climate change. However, this does not give a straight idea about the environmental relevance of the impact, overall not for decision-makers without an LCA background. For this reason, LCIA at endpoint level offers indicators that are more understandable and damage-oriented. Here, the midpoint indicators are further aggregated in the three Areas of Protection *Human health*, *Natural environment* and *Natural resources* (see Figure 4). The CO_2 eq. from the midpoint indicator add, e.g. to *Human health* but are now expressed as Disability Adjusted Life Years (DALYs). As such, the relevance of GHG for human health becomes more understandable.

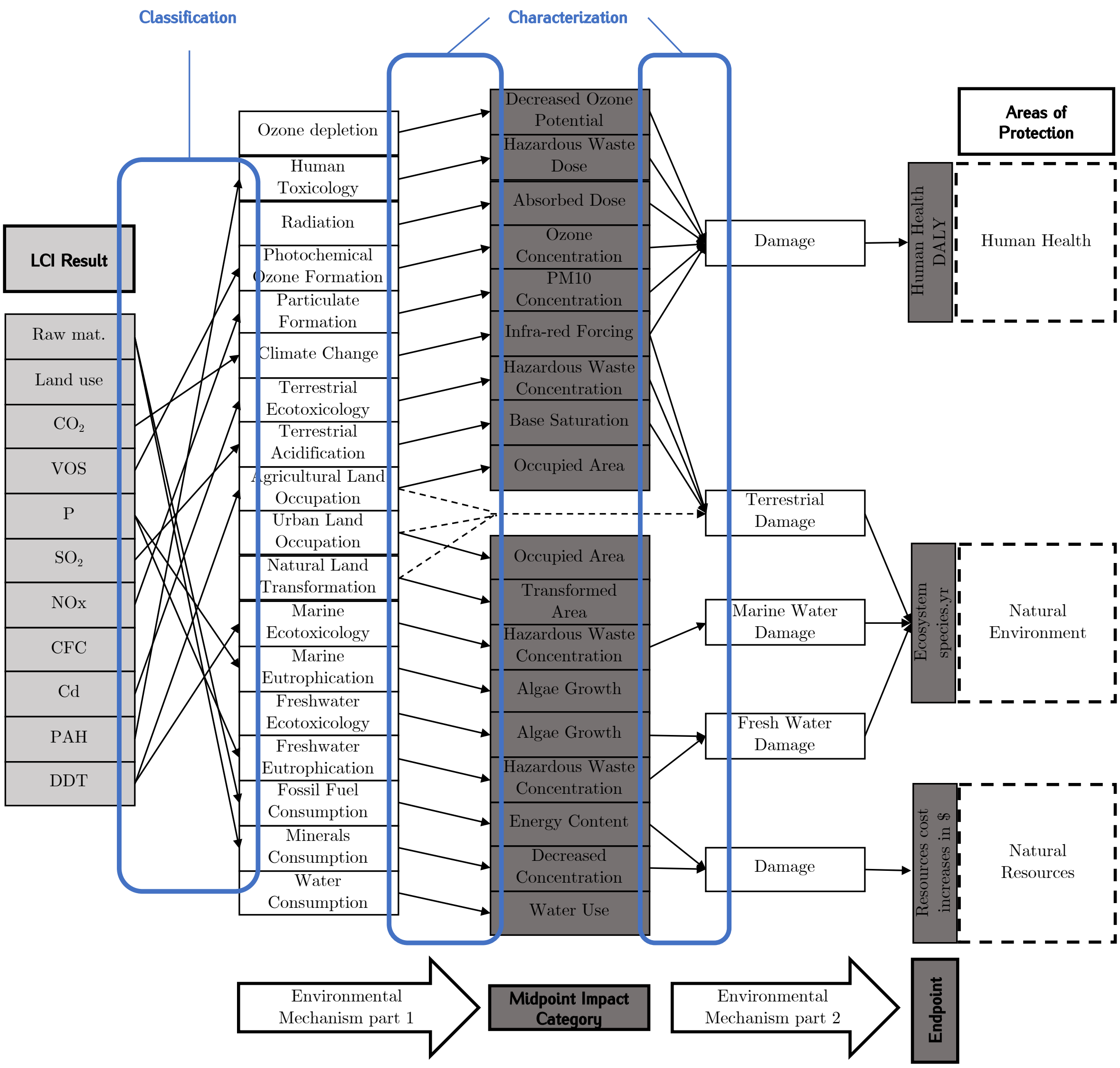


Figure 4 Exemplary modelling pathways from LCI to midpoint and endpoint impact categories according to the ReCiPe method (figure modified from Goedkoop et al. (2009)).

The (EC-JRC, 2010) recommends using an iterative approach while performing an LCA. At every step of the study, the preliminary findings are interpreted and evaluated in terms of their sensitivity, consistency and completeness, i.e. whether the results match the initial model or whether goal and/or scope need to be redefined. Subsequent fine-tuning becomes necessary when the initial knowledge of the assessed product is broadened and new aspects need to be taken into account or when difficulties with finding reliable data occur. Precise initial goal and scope definitions are necessary though it is possible that these will be modified in the course of the LCA (EC-JRC, 2010).

Two principles can be applied when performing an LCA: attributional and consequential modelling. Attributional modelling is used to describe a product's environmental impact over the whole life cycle. The product is modelled in its current state or how it is planned. Specific data for manufacturing, operation and EoL phases should be used. Attributional modelling is also used for product comparisons. Consequential modelling is not focusing on a specific state but is rather change-oriented on a larger scale. It assesses in how far decisions taken in a foreground system affect the market or consumer behaviour (EC-JRC, 2010). In consequential LCA studies the so-called rebound effect can be included (Font Vivanco and van der Voet, 2014; Weidema et al., 2009). The rebound effect describes direct and indirect effects of products or services on individual or collective consumption or production patterns (Greening et al., 2000). According to Brander and Ascui (2015, p. 99), the GHG Protocol as the standard for corporate GHG inventories is "attributional in nature". Hence, attributional LCA studies are used as a data basis in corporate carbon management.

2.2 OEMs' corporate carbon management

In this section, the current state of knowledge on physical corporate carbon management is presented. Here, sub-research question 1 ("What are existing carbon management approaches of OEMs?") is addressed. This section is structured in sub-chapters distinguishing between carbon accounting and controlling. The distinction is necessary as data derived from corporate carbon accounting serves as a basis for calculating corporate carbon reduction targets while corporate carbon controlling incorporates the future-oriented perspective on companies' absolute carbon emissions. Following a general introduction to the research field, the focus is laid on carbon management in the automotive industry.

Development of corporate carbon management
Corporate carbon management was developed as a sub-discipline of environmental management as the focus of legislators, scientists and the general public shifted towards the emission of GHG and their effect on climate change. With the introduction of emissions trading systems like the European Cleaner Development Mechanism and increasing pressure to disclose carbon-related information, research on corporate carbon management gained increasing attention (Burritt et al., 2011). As a consequence, carbon management approaches are mainly derived from the preceding environmental managements research.

In this field, Environmental Management Accounting (EMA) has become the main framework to ensure the quality of corporate environmental management, which involves collecting physical and monetary information related to corporate impacts on the natural environment (Burritt et al., 2002; Qian et al., 2018). Within the EMA, the collected information is not only carbon-related but includes information on other non-GHG emissions to air, water and soils. As the collection of carbon-related information is part of environmental management information systems, approaches for gathering and methodologies for estimating carbon emissions can and should be transferred into carbon information systems (Burritt et al., 2011).

Definitions
Corporate carbon management is described as "[…] activities related to the coordination of activities to achieve a resource-efficient […] and effective reduction of carbon emissions" (Zvezdov and Schaltegger, 2015, p. 29). Corporate carbon management thus comprises all corporate activities needed to ensure a reduction of corporate carbon emissions and serves as a collective term for the subordinate terms described in the following. Busch and Schwarzkopf (2013) introduce the life-cycle perspective to the research field by defining corporate carbon management as reducing a firm's impact on climate change through life-cycle wide carbon reduction efforts and carbon offsetting[2]. Although corporate carbon management often refers to a physical and monetary dimension, the term only refers to physical carbon management in this dissertation.

Corporate carbon management comprises all activities related to effectively reducing corporate GHG emissions along the life cycle of products and services offered.

The basis for corporate carbon management is gathering carbon-related information, i.e. creating an inventory of GHG emissions (Alvarez, 2012). The corresponding term *carbon accounting* refers the collection and summary of corporate carbon emissions (Tang and Luo, 2014). In Stechemesser and

[2] Carbon offsetting refers to organizations buying emission credits from projects preventing, reducing or capturing carbon emissions (Lovell et al., 2009).

Guenther (2012, p. 27), Hespenheide et al., (2010) define carbon accounting as “the activity of measuring carbon emissions and removals and retaining an ongoing inventory of operations-based emissions”. A corporate carbon footprint, i.e. the summary of absolute direct and indirect carbon emissions, is estimated which can be disclosed to the public. Carbon accounting is inherently past-oriented as GHG emissions caused during the reporting year are gathered. The accounted carbon information can serve for monitoring the development of a company’s GHG emissions over time, either for internal or external purposes or both. The purely physical approach towards carbon accounting taken in this study has been already been pursued in seven publications which were listed by Stechemesser and Guenther (2012).

Corporate carbon accounting comprises all activities related to gathering carbon-related information on direct and indirect GHG emissions.

The information generated in the carbon accounting phase can be used to take strategic decisions concerning the reduction of corporate GHG emissions in the future. *Carbon controlling* describes the addition of a strategic perspective to pure monitoring of past carbon emissions (Günther and Stechemesser, 2010). A strategic decision is related to setting a corporate reduction target, developing corresponding carbon-reducing measures and support implementing them in the company (Schaltegger et al., 2015). Estimating the impact of carbon-reducing measures on future emissions is only possible if future corporate GHG emissions are projected, i.e. if future emission scenarios are developed based on past emissions (Schaltegger and Csutora, 2012). Carbon controlling therefore also encompasses modelling future GHG emission trajectories. To internally monitor the effectiveness of reduction measures and support their implementation, Key Performance Indicators (KPI) can be set up (Busch, 2010; Zvezdov and Schaltegger, 2015). KPIs are therefore related to both past accounted and future modelled carbon emissions. A target KPI is derived based on the overall carbon reduction target and the yearly/monthly/etc. reported KPI shows the company’s past emissions performance in relation to the target. Although carbon controlling depends on past emissions data, it is also future-oriented as strategies to improve the future corporate carbon performance are developed.

Corporate carbon controlling comprises all activities related to taking strategic decisions concerning the future reduction of direct and indirect GHG emissions.

Figure 5 shows a framework of corporate carbon management which illustrates the relations between carbon accounting and controlling as well as their respective outputs.

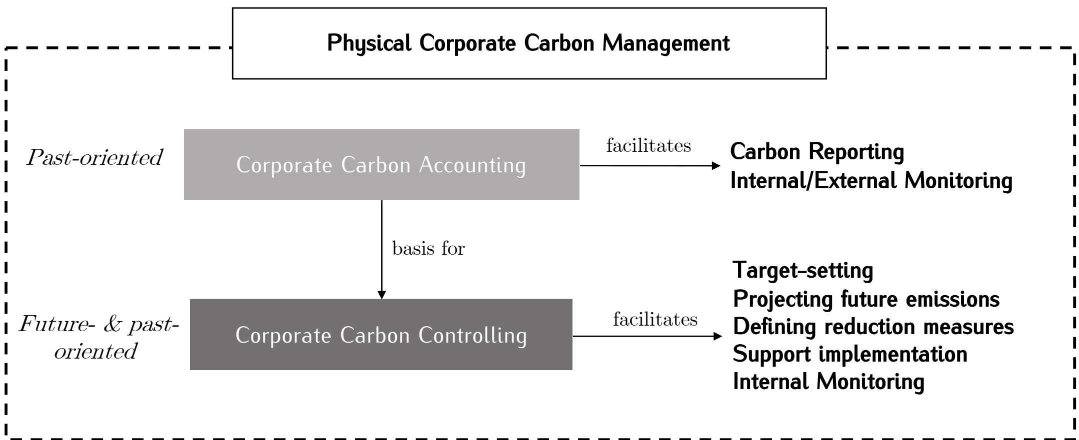


Figure 5 Physical corporate carbon management framework.

Schaltegger et al. (2015) propose to connect activities facilitated within carbon management along the steps of the management cycle as introduced by e.g. Glienke and Guenther (2016). As such, the sequence of actions within corporate carbon controlling is revealed. Figure 6 depicts the Management Circle according to ISO 14001 extended with the respective carbon management activities pursued at each stage, it is therefore named “Carbon Management Circle”. In this illustration, the element of *corporate policy* starts the sequence as the board needs to commit to a certain corporate goal like, e.g., bringing all corporate activities in line with the requirements of a 2 °C target. According to Pinkse and Busch (2013) this commitment can be referred to as a corporate carbon norm. In this example, the carbon norm is “becoming a 2 °C – compatible company”. In case this carbon norm is externally communicated, it can serve the purpose of creating a desired future image of the company for external stakeholders or of differentiating the company from competitors (ibid.). The board’s commitment is accompanied by a mandate for the company’s sustainability practitioners to develop an adequate carbon reduction pathway and reduction measures.

In the *corporate planning* stage this mandate is realized by transferring the proclaimed corporate carbon norm into the company-specific CO_2-reduction pathway. Subsequently, future emissions are modelled and carbon-reduction measures evaluated (Schaltegger and Csutora, 2012). *Implementation and operation* refers to activities related to setting up a new carbon-controlling department as recommended by Burritt et al. (2011) or organising process and information flows needed to achieve a timely implementation of chosen measures. *Checking and corrective action* involves monitoring the effectiveness of implemented measures by carbon management practitioners. At this point, the company’s carbon performance is checked via one or several corporate carbon indicators, i.e. KPIs (Busch, 2010). In case the targeted carbon reduction was not achieved, corrective actions can be proposed. In the following *management review* decisions are taken concerning possible corrective actions or a recommendation to enhance the board’s mandate. Although not explicitly stated, carbon accounting activities deliver the data basis for corporate planning and checking and corrective action stages and are thus indispensable for corporate carbon management. Stechemesser and Guenther (2012, p. 31) state that “carbon accounting […] can be the basis for emissions reductions […]”. Accordingly, Murthy and Parisi (2013) recommend to base future carbon emissions scenarios on past emissions data.

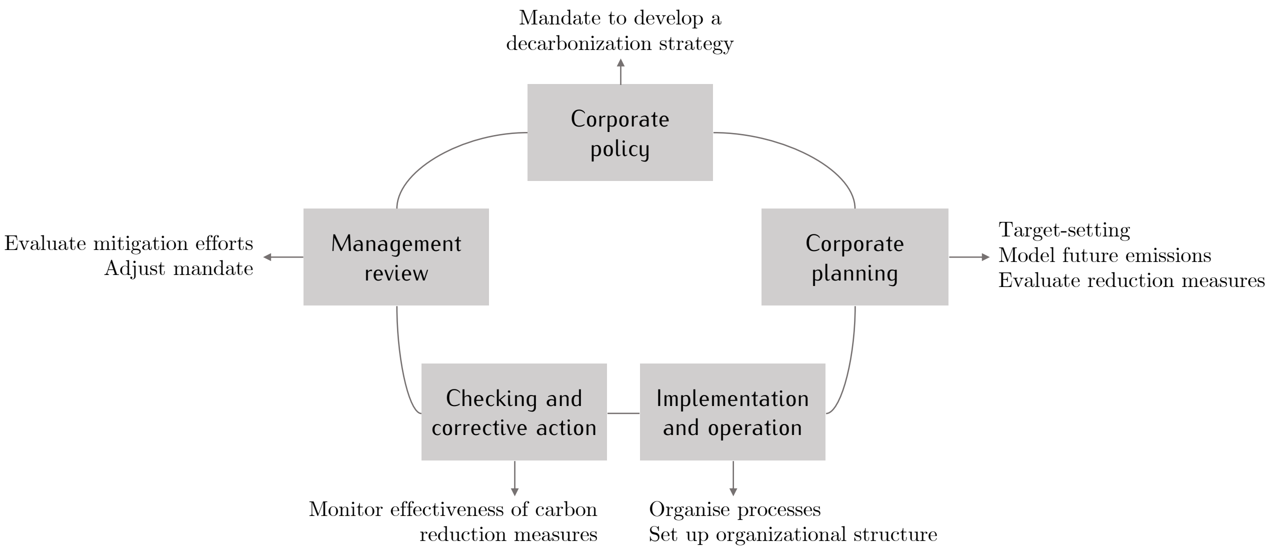


Figure 6 Carbon Management Circle (based on Schaltegger et al.).

Burritt et al. (2011) developed another framework called Carbon Management Accounting (CMA) which serves as a well-established guide for classifying corporate management approaches and the respective information needed by managers. The authors do not distinguish between carbon accounting and carbon controlling as defined above but mainly differentiate between short- and long-term as well as past- and future-oriented carbon management approaches which are all referred to as “physical carbon

accounting" (Table 1). Next to physical carbon accounting, Burritt et al. (2011) also analysed financial carbon accounting by adding a monetary dimension to carbon-related information. As the focus of this dissertation is on physical carbon management, financial aspects of CMA are not further discussed.
Past-oriented carbon management approaches either monitor the carbon performance of a company (i.e. carbon accounting) or evaluate ex post the effect of CO_2-reduction measures on the corporate carbon performance. Future-oriented CMA approaches forecast corporate GHG emissions and the effect of carbon-reduction measures on these future emissions. They can thus be allocated to carbon controlling approaches. The differentiation in approaches relying on routinely generated versus ad hoc information is based on empirical findings of carbon management practices in companies. Burritt et al. (2011) recommend however to use routinely generated information in order to work in a resource-efficient way. According to the authors, past-oriented CMA approaches dominate the corporate practice though they highlight the need for future-oriented approaches.

Table 1 Dimensions of physical carbon management according to Burritt et al. (2011)

		Short-term	**Long-term**
Past-oriented	Routinely generated information	Carbon-flow accounting (e.g. collecting daily emissions of production processes)	Carbon capital impact accounting (e.g. modelling absolute emissions reduction over 10 years)
	Ad hoc information	Ex post assessment of short-term carbon impacts (e.g. collection of saved travel miles within a short-term carbon-reduction program)	Ex post assessment of physical carbon investment appraisal (e.g. calculation of achieved carbon reduction through implementation of new logistics network)
Future-oriented	Routinely generated information	Physical carbon budgeting (e.g. expected reduction in CO_2 of a commercial building through awareness training of staff)	Long-term physical carbon planning (e.g. expected from projects developed by the research and development department)
	Ad hoc information	Carbon impact budgeting (e.g. consideration of CO_2 reduction effect in the next accounting period)	Physical environmental investment appraisal (e.g. calculation of total CO_2 reduction effect of clean production investment)

Frame of reference "corporate carbon management"
Based on the introduction to corporate carbon management above, the frame of reference of this dissertation regarding this research field is defined. As the research objective is to develop a method that facilitates evaluating the impact of CO_2 reduction measures along the life cycle of vehicles and mobility services on OEMs' absolute CO_2 emissions to support reaching reduction targets, both the measurement of past emissions and modelling of future emissions is of interest. Therefore, carbon accounting as well as carbon controlling is further assessed in the following. Understanding how corporate GHG inventories of past carbon emissions are generated is crucial as this data serves as the basis for setting reduction targets, projecting future emissions and evaluating respective reduction measures (Damert et al., 2017; Günther and Stechemesser, 2010). Carbon accounting is, however, already bound to standards like the GHG Protocol (WBCSD and WRI, 2004). Therefore, no new carbon accounting methodology needs to be developed. Though Burritt et al. (2011) stress that activities related to corporate carbon management need to be compatible with existing information systems so that routinely generated carbon-related information can be used. The new methodology therefore depends on data derived by carbon accounting.

Activities included in carbon controlling which address the research objective of this dissertation are setting reduction targets, projecting future emissions and evaluating respective reduction measures. According to the Carbon Management Circle (Figure 6), these are activities in the *Corporate Planning* stage. Setting a carbon reduction target in line with the Paris Agreement is facilitated externally, for example, by using approaches published by Science Based Targets initiative (SBTi). Hence, the to-be-developed method must be compatible with scope and assumptions pursued in the target-setting approach.

Projecting future emissions and evaluation of reduction measures is the main research objective. Setting up organisational structures to operationalise recommended reduction measures within the company is outside of the frame of this research. Likewise, monitoring the effectiveness of carbon reduction measures is not included in the new methodology as past emissions data is already collected and reported. Though, the new method needs to be compatible in scopes and calculation approaches used. Therefore, this data will be used during the "reality check" of forecasted emissions by comparing it to reported emissions. Neither is the development of a KPI to track progress towards achieving a reduction target part of this study. However, the new method should provide connecting factors to derive a KPI from the modelling results.

According to the CMA framework by Burritt et al. (2011), the to-be-developed method includes traits of a past- and future-oriented and long-term physical carbon management approach which relies on routinely generated data. The purpose of any CMA approach is "providing managers with information that assists corporate decision-making related to carbon emissions" (Zvezdov and Schaltegger, 2015, p. 29). Related to the research objective, the purpose of this study is to provide managers with a modelling method that assists decision-making concerning the achievement of a corporate 2 °C target. Figure 7 illustrates the frame of reference of carbon management activities included in the new methodology.

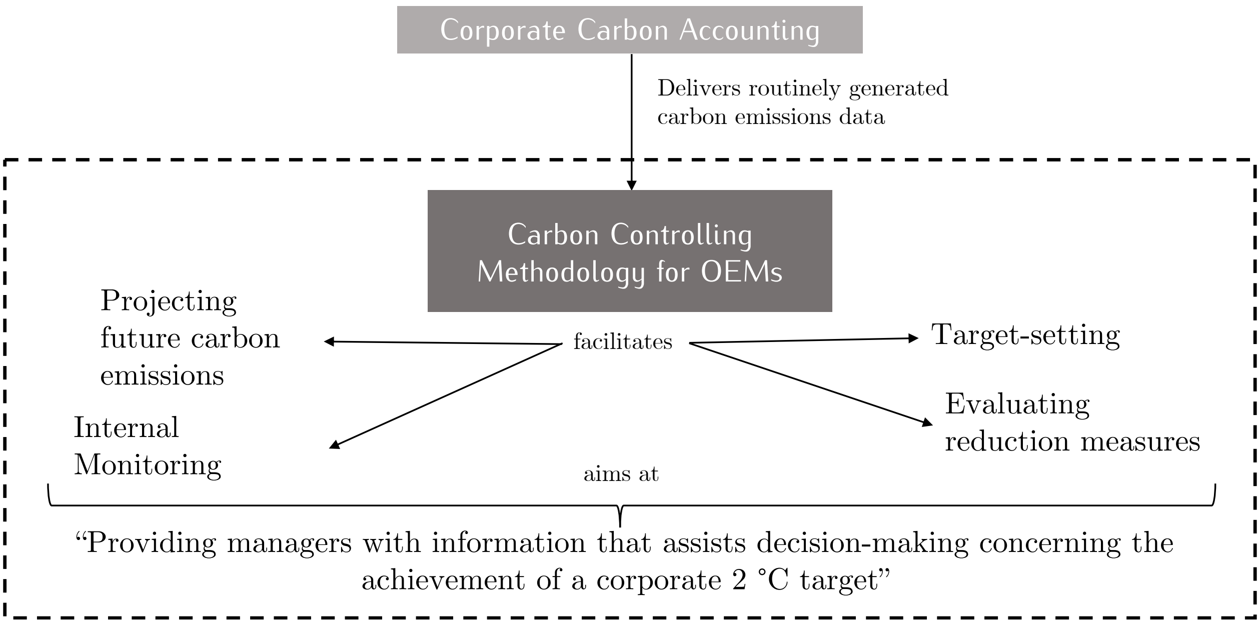


Figure 7 Frame of reference "Corporate Carbon Management" in this dissertation.

2.2.1 Corporate Carbon Accounting

Carbon emissions data generated via corporate carbon accounting provides the basis for managers to monitor a company's absolute carbon emissions internally and, if reported externally, for stakeholders to evaluate a company's carbon mitigation efforts (Qian et al., 2018). CDP oversees the most extensive data base on voluntarily reported carbon emissions data. Busch and Lewandowski (2017, p. 747) describe CDP as "the most popular voluntary reporting scheme […]". In 2017, over 1,000 companies worldwide published their GHG emissions on CDP websites (CDP, 2018b). This includes the ten top-selling OEMs (CDP, 2018a; Forbes, 2017). Rising numbers of companies disclosing their carbon emissions is backed by Gibassier (2015) who describes a growing interest in corporate carbon information and mitigation activities by stakeholders and managers.

In the following, the scope of carbon emissions accounted for and reported by companies is described by means of the GHG Protocol and relevant scientific literature (WBCSD and WRI, 2004). The analysis of scope and assumptions taken to generate a corporate GHG inventory is necessary in order to derive methodological requirements for the new method to be compatible with accounted carbon information.

Guidance for creating and reporting a corporate GHG inventory

The starting point for any corporate carbon management activity is setting up the annual GHG inventory of a firm (Damert et al., 2017). A GHG inventory includes six greenhouse gases referred to in the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (WBCSD and WRI, 2004). Carbon emissions covered in the GHG inventory are not restricted to a firm's own production processes, but include emissions caused during use and EoL phases, i.e. recycling and disposal activities. Including carbon emissions arising over the complete life cycle of products and services in corporate GHG inventories is discussed as appropriate scope by carbon management researchers (Alvarez, 2012; Navarro et al., 2017; Stechemesser and Guenther, 2012). Weidema et al. (2008) use the term *carbon footprint* instead of GHG inventory and introduce LCA as suitable methodology to create the carbon footprint. The life-cycle approach for accounting GHG emissions is reflected in the GHG Protocol which serves as a standard for corporate carbon accounting and reporting (Stechemesser and Guenther, 2012).

GHG Protocol is a cooperation between World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) and publishes the Corporate Accounting and Reporting Standard since 2001. GHG Protocol is one verification standard accepted by CDP which discloses accounted carbon emissions of corporations, institutions and cities to the public (CDP, 2018c). The vast majority of Fortune 500 companies (>90%) reporting emissions to CDP choose GHG Protocol as source for generating their GHG inventory (GHG Protocol, 2018). The generation and preparation of carbon-related information, i.e. the creation of a GHG inventory is thus guided by a verified standard. Subsequent disclosing and rating of the GHG inventory is executed by CDP (Figure 8).

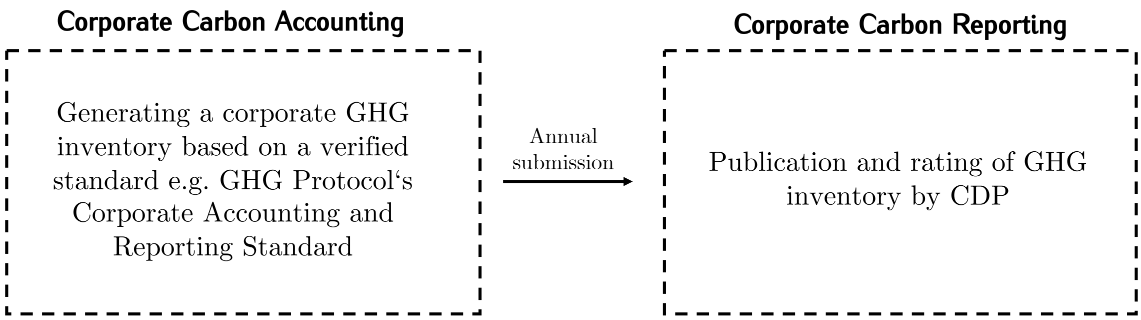


Figure 8 GHG inventory as prerequisite for CDP reporting.

The Corporate Accounting and Reporting Standard is based on five principles which draw on financial accounting standards (Stechemesser and Guenther, 2012; WBCSD and WRI, 2004). According to Zvezdov and Schaltegger (2015) these principles are accepted by environmental management researchers. They are summarised in Table 2.

Table 2 Principles of GHG accounting and reporting according to WBCSD and WRI (2004)

Principle	**Explanation**
Relevance	Ensure the GHG inventory appropriately reflects the GHG emissions of the company and serves the decision-making needs of users – both internal and external to the company.
Completeness	Account for and report on all GHG emission sources and activities within the chosen inventory boundary. Disclose and justify any specific exclusions.
Consistency	Use consistent methodologies to allow for meaningful comparisons of emissions over time. Transparently document any changes to the data, inventory boundary, methods, or any other relevant factors in the time series.
Transparency	Address all relevant issues in a factual and coherent manner, based on a clear audit trail. Disclose any relevant assumptions and make appropriate references to the accounting and calculation methodologies and data sources used.
Accuracy	Ensure that the quantification of GHG emissions is systematically neither over nor under actual emissions, as far as can be judged, and that uncertainties are reduced as far as practicable. Achieve sufficient accuracy to enable users to make decisions with reasonable assurance as to the integrity of the reported information.

The principle *relevance* refers to choosing the appropriate organizational and respective inventory boundary. For example, a group with total financial and operational control over its companies would account for 100% of GHG emissions whereas groups holding equity shares in other companies account only for the respective share of GHG emissions (WBCSD and WRI, 2004). According to Schaltegger et al. (2015), establishing company-specific implications for a *relevant* GHG inventory is challenging as future developments in carbon legislations or perception of the topic by the public is hardly predictable.

Completeness refers to the next step: accounting all GHG emissions within the organizational boundary. The standard divides GHG emissions caused over the life cycle of products and services not according to life-cycle phases but to three scopes. Scope 1 emissions refer to direct GHG emissions: emissions caused by, e.g. generating electricity on the factory site. Scope 2 emissions refer to indirect energy-related GHG emissions, i.e. emissions arising from purchasing electricity. Scope 3 emissions refer to other indirect GHG emissions. An overview of scope 1-3 emissions is presented in Figure 9.

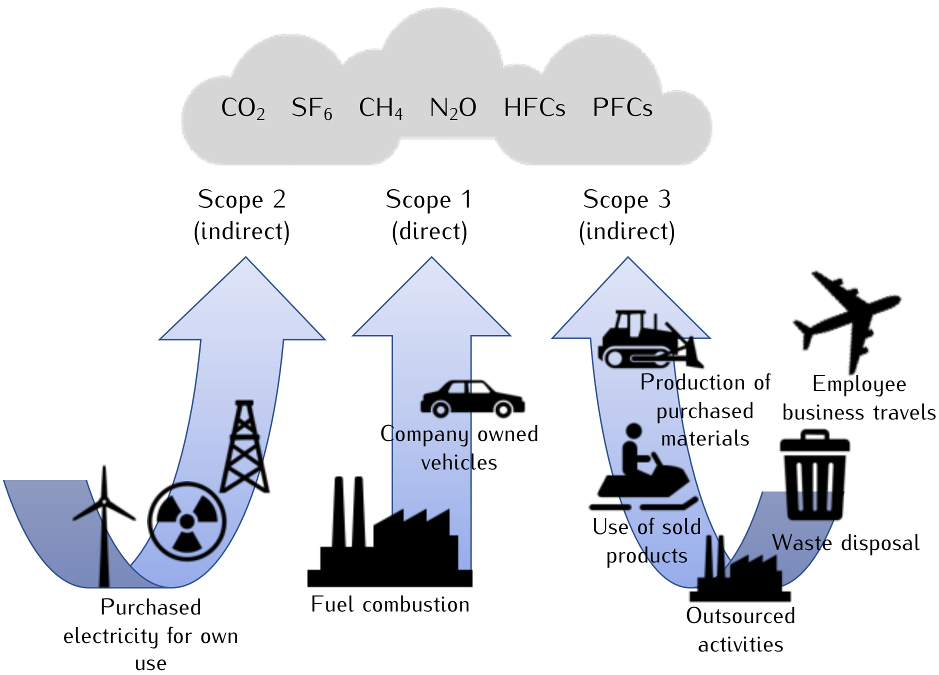


Figure 9 Overview of scope 1, scope 2, and scope 3 (incomplete) emissions according to WBCSD and WRI, 2004.

The complete list of scope 3 emission sources according to CDP (2018e) is provided below.

Table 3 Scope 3 emissions categories according to CDP (2018e).

Scope 3 categories	Denomination
1	Purchased goods and services
2	Capital goods
3	Fuel and energy related activities (not included in scope 1 or 2)
4	Upstream transportation and distribution
5	Waste generated in operations
6	Business travel
7	Employee commuting
8	Upstream leased assets
9	Downstream transportation and distribution
10	Processing of sold products
11	Use of sold products
12	End of life treatment of sold products
13	Downstream leased assets
14	Franchises
15	Investments
16	Other (upstream)
17	Other (downstream)

Excluding some of these categories from the GHG inventory and reporting is possible while following the *completeness* principle. Schaltegger et al. (2015, p. 16) refer to this principle as "conflicts between information completeness and task simplicity". For example, Daimler reports emissions for 13 of the categories (Daimler, 2018a), Volkswagen and Toyota for twelve (Toyota, 2017; VW, 2018a). According to Stechemesser and Guenther (2012), carbon footprints become more precise the higher the accounting threshold but increase the accounting effort in the same manner.

Consistency of e.g. inventory boundary and calculation methodologies is important both internally for managers and externally for stakeholders. Though Schaltegger et al. (2015) state that the GHG protocol does not offer guidance on completely eliminating inconsistencies. Likewise, Andrew and Cortese (2011) criticize that non-standardised carbon reporting methods impede the comparability of reported emission performances. GHG Protocol demands *transparency* of methods and assumptions used to calculate the GHG inventory. Again, Schaltegger et al. (2015) note that the protocol does not give guidance on how to estimate carbon emissions for each category. Therefore, establishing transparency of calculation methods is crucial for external stakeholders to judge a firm's carbon mitigation efforts and compare them across companies. *Accuracy* is the last principle described by GHG Protocol which summarises on the previous principles. Only if *complete* emissions within the *relevant* inventory boundary are *consistently* accounted for in a *transparent* way, can an accurate GHG inventory be calculated which does not over or underestimate carbon emissions.

Drawing on generally accepted accounting principles of the finance sector, Ortas et al. (2015) introduce the additional principle of *conservativeness* in carbon accounting. In case carbon calculation methodologies do not deliver reliable results or carbon-related data is scarce, GHG emissions should be estimated in a conservative manner. Compliance with accounting principles can be reviewed by external accounting organizations which lack of has been criticized by Perrault Crawford and Clark Williams (2010) for sustainability reporting in general.

OEMs' carbon accounting

CDP offers specific guidance for carbon emissions reporting of OEMs selling Light-Duty Vehicles (LDVs) (CDP, 2018d). OEMs must respond to the full version of the CDP questionnaire covering scope 1-3 emissions. The questionnaire further includes sector-specific questions on scope 3 category 11 ("use of sold products"). CDP's focus on OEM's carbon emissions arising during the use phase of sold products is comprehensible as the majority of scope 1-3 emissions is caused by the use of sold vehicles. The use phase refers to well-to-wheel emissions, i.e. carbon emissions caused in fuel and energy supply chains ("well-to-tank") as well as tailpipe emissions ("tank-to-wheel"). Shares of reported scope 1-3 emissions of VW AG, BMW AG and Daimler AG in 2016 are depicted in Table 4 showing the relevance of scopes and categories on absolute emissions.

Table 4 Scope 1-3 emissions as well as number of sold vehicles reported to CDP by VW AG, BMW AG and Daimler AG for reporting year 2016 (CDP, 2018d). Note the scope 3 cat. 11 contribution of ≥ 70%.

Scope (and categories)	**Explanation**	**Share of emissions VW 2016 [%]**	**Share of emissions BMW 2016 [%]**	**Share of emissions Daimler 2016 [%]**
Scope 1	Direct energy-related emissions	1.3	0.8	1.4
Scope 2 (market-based)	Indirect energy-related emissions	1.6	1.2	2.4
Scope 3				
1	Purchased goods and services	17.6	21.6	19.9
2	Capital goods	4.1	Not relevant	Not relevant
3	Fuel and energy related activities (not included in scope 1 or 2)	<1	Not relevant	<1
4	Upstream transportation and distribution	1.1	2.0	<1
5	Waste generated in operations	<1	Not relevant	1.1
6	Business travel	<1	<1	<1
7	Employee commuting	<1	<1	<1
8	Upstream leased assets	Not relevant	Not relevant	n.a.
9	Downstream transportation and distribution	Not relevant	Not relevant	<1
10	Processing of sold products	<1	Not relevant	<1
11	Use of sold products	71.6	71.5	70.0
12	End of life treatment of sold products	<1	1.7	1.3
13	Downstream leased assets	<1	<1	Not relevant
14	Franchises	<1	Not relevant	<1
15	Investments	Not relevant	Not relevant	Not relevant
16	Other (upstream)	Not relevant	Not relevant	Not relevant
17	Other (downstream)	Not relevant	Not relevant	Not relevant
Total		100	100	100
Absolute emissions 2016 [t CO2-e]		337,573,339	71,436,320	77,957,000
Number of sold vehicles 2016		10,205,000	2,367,603	2,197,956

Although the three OEMs do not report emissions for all the same categories (cat.), carbon hotspot cat. are the same. The by far most relevant scope 3 cat. is number 11 representing the use phase of sold vehicles which adds up to at least 70% of absolute emissions reported for VW AG, BMW AG and Daimler AG. It is followed by cat. 1 which indicates emissions caused in the material supply chains of produced vehicles. The share on overall emissions ranges from 18% (VW AG) to 22% (BMW AG). VW AG reports a 4% share of emissions caused through capital goods whereas Daimler AG and BMW AG classify this category as “not relevant”. All other reported scope 3 cat. of the three OEMs make up 2% or less of absolute emissions. Scope 1 and scope 2 emissions are reported by all three as demanded by CDP. Summed, scopes 1 and 2 make up under 4% of total emissions reported by VW AG, BMW AG and Daimler AG.

Absolute reported emissions are positively correlated with the number of sold cars. VW AG sold roughly 80% more vehicles in 2016 than BMW AG and Daimler AG each. Likewise, VW AG’s absolute emissions are roughly 80% higher than BMW AG’s and Daimler AG’s reported emissions, respectively.

Additionally to the amount of carbon emissions, OEMs provide information on their calculation methodologies (CDP, 2018a). All three OEMs indicate that scope 1 emissions are calculated based on energy consumption data directly measured on their production sites via environmental information systems. Scope 2 emissions are calculated based on country-specific or averaged emission factors. This approach is in line with Burritt et al. (2011), who recommend to use data from existing information systems to calculate the carbon footprint in order to work in a resource-efficient way.

The use phase of sold vehicles is distinguished in well-to-tank (WWT) emissions, i.e. fuel supply chains, and tank-to-wheel (TTW) emissions, i.e. emissions caused directly while driving the vehicles. The OEMs calculate cat. 11 based on reported market-specific fleet averages (g CO_2/km), the number of vehicles sold in each market and an assumed lifetime kilometrage of 150,000-200,000 km per vehicle. Daimler AG and VW AG indicate that WTT emissions are calculated separately. VW AG specifies that fuel production emissions are calculated differentiated by markets, similar to the calculation of TTW emissions.

The second carbon hotspot (cat. 1), the material supply chains, are calculated based on vehicle LCA studies for all three OEMs. Navarro et al. (2017) and Schaltegger and Csutora (2012) also state that LCA is valid tool to calculate downstream carbon emissions. BMW AG reports that emissions relevant for cat. 1 are separated from carbon emissions caused over the life cycle of the assessed vehicle in the LCA study. Similarly, Daimler AG indicates to separate scope 1 and 2 emissions (termed “in-house production”) from carbon emissions calculated for the manufacturing phase of the assessed vehicle within LCA studies. The OEMs state that there are not specific LCAs for all models sold. Therefore, models missing an LCA are assigned a comparable LCA of a similar model. Daimler AG assigns LCAs based on the production platform whereas VW AG sets up vehicle classes like “Compact” and “Fullsize” and assigns emission factors derived on a vehicle-mass basis [kg CO_2-e/kg vehicle-mass]. According to BMW AG and VW AG, final cat. 1 emissions are calculated by multiplying vehicle classes with the respective sales volumes. Daimler AG, VW AG and BMW AG report that cat. 12, i.e. emissions caused during the EoL phase, is calculated with the same approach as category 1: a sales-weighted emissions figure based on EoL emissions of vehicle LCA studies.

The carbon accounting approaches described above for scopes 1 and 2 as well as scope 3 categories 1, 11 and 12 are used to calculate more than 90% of absolute emissions reported by BMW AG, Daimler AG and VW AG (see Table 4). These figures represent carbon emissions caused over the whole life cycle of vehicles covering manufacturing, use and EoL phases comparable to emission covered in a standard vehicle LCA. The remaining scope 3 categories are only partially reported and are labelled “not relevant” except VW AG’s cat. 4. These categories account for emissions not usually included in LCA studies of products. Accordingly, these emissions are not calculated via LCA studies but are accounted for via e.g.

empirical studies on employee commuting behaviour (VW AG, BMW AG) and averaged emission factors (Daimler AG) (cat. 7).

Figure 10 shows the approach by VW to facilitate efficient carbon-related data collection. While scope 1 and 2 emissions are directly gathered from existing environmental information systems, scope 3 emissions are mainly calculated via vehicle LCAs and extrapolated to fleet levels. According to Warsen (2013), 96% of total carbon emissions caused by activities of VW AG can be quantified based on LCA studies of specific vehicles. In corporate carbon accounting, midpoint LCIA results are used as the amount of carbon emissions (e.g. kg CO_2 eq.) caused over the life cycle of products and services is taken to generate the GHG inventory and to subsequently forecast future GHG emissions. The environmental relevance of these emissions, e.g. the impact on the *Natural environment* are not assessed.

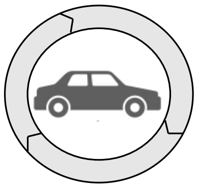
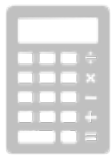
	Scope 1 & 2	**Scope 3**	
		E.g. supply chain, recycling	E.g. business travel
Data source	 Existing environmental information systems	 Sales-weighted LCA studies of vehicles per segment	 Other data sources

Figure 10 VW Group data sources used for carbon accounting.

Next to reporting the GHG inventory, CDP asks companies to disclose information on their CO_2 reduction targets and rates them accordingly (CDP, 2017). These ratings are included in RobecoSAM's Corporate Sustainability Assessment which provides the data basis for the Dow Jones Sustainability Index (DJSI) (RobecoSAM, 2017). According to Searcy and Elkhawas (2012), DJSI is one of the most credible sustainability indices linked to the financial market. Carbon management as well as setting and reaching carbon-reduction targets are thus not merely a sign of goodwill on the part of OEMs but are becoming a business case. For example, in a meta-study of carbon-reporting companies Busch and Lewandowski (2017, p. 745) found that a "good carbon performance is generally positively related to superior financial performance".

2.2.2 Corporate Carbon Controlling

In corporate carbon controlling, past carbon emissions are used as a starting point to derive strategic decisions concerning the carbon performance of the company (Günther and Stechemesser, 2010; Tang and Luo, 2014). As defined in the frame of reference for carbon management (Figure 7), the scope of this dissertation includes developing an integrated method to project future emissions and to evaluate carbon reduction measures regarding the achievement of a specific target. Additionally, it should be possible to use past emissions data to monitor the effectiveness of implemented carbon reduction activities.

Although corporate carbon management has received increasing attention over the past decade scientists have missed to transfer theory into practical approaches for managers. Luo and Tang (2016) state that research on the quality of corporate carbon management systems is lacking. Qian et al. (2018) strengthen this point by stating that practical approaches of carbon management remain under-researched. And Zvezdov and Schaltegger (2015, p. 41) even call broadening the existing set of carbon management tools a "central challenge". Maas et al. (2016) express the need for integrating different environmental management approaches to increase their effectiveness in reducing environmental impacts of firms which includes carbon emissions. Moreover, Pinkse and Busch (2013) express the need for effective carbon management tools by revealing that companies can face a consumer backlash if a communicated carbon emissions target or norm is not authenticated by respective measurable reductions of carbon emissions.

Tang and Luo (2014) therefore developed the Carbon Management System (CMS), a tool that aims at operationalizing a company's carbon policy. CMS is structured along four perspectives which are based on the requirements of ISO 14001 standards for environmental management systems. A schematic depiction of the tool is shown in Figure 11. The first perspective *carbon governance* addresses organizational issued such as the establishment of a Board that develops the carbon policy, assesses risks and opportunities and monitors its implementation. The second perspective *carbon operation* includes the activities target-setting, implementation of reduction measures and supply chain emissions control. The authors recommend to perform these activities via cradle-to-grave life-cycle analysis. *Emissions tracking and reporting* perspective involves carbon accounting and carbon insurance, i.e. external verification of the GHG inventory following the *Accuracy* principle of GHG Protocol. The last perspective *Engagement and disclosure* is directed at communicating the annual GHG inventory to external stakeholders.

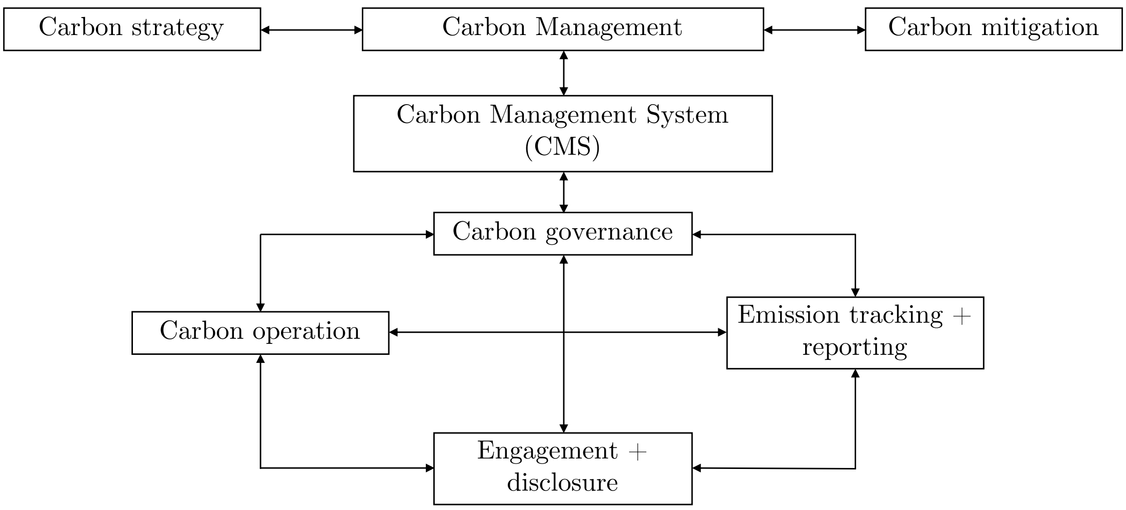


Figure 11 Carbon Management System according to Tang and Luo (2014).

Although the authors call CMS a tool that is supposed to bring together strategy and carbon mitigation it remains theoretical. For example, no specifications concerning how targets should be set or reduction measures evaluated are given. Its support for actually modelling emissions and effects of reduction measures is therefore limited. Additionally, Tang and Luo (2014) admit that it remains challenging for managers to identify core elements of CMS to achieve strategic carbon reduction goals. In line with Burritt et al. (2011), the authors point out that carbon management frameworks or tools are hardly applicable across industrial sectors but that modifications are needed according to specific requirements of a sector or company. To the author's knowledge no specific carbon controlling method or tool for OEMs exists.

2.2.3 Setting Paris Agreement-compatible corporate carbon reduction targets

Several approaches to set Paris Agreement-compatible CO_2-reduction targets have been developed. However, mitigation strategies are mainly developed on the national level and not on the company level (Krabbe et al., 2015). As mentioned in the introduction, several OEMs have publicly committed themselves to at least a 2 °C-compatible carbon reduction targets verified by the Science Based Targets initiative (SBTi) (SBTi, 2018a). Up to date, over 200 companies have set CO_2 reduction targets based on one of the approaches provided by the initiative (SBTi, 2019a). Some companies, like Ford Motor Company, pursue carbon reduction targets which seemingly align with Paris Agreement requirements, but are not transparent with the underlying calculation methodology (Ford, 2015; Krabbe et al., 2015). As the goal of this dissertation is not to develop an approach to calculate Paris Agreement-compatible reduction targets for OEMs but rather to support OEMs in strategic decision-making to comply with set targets, SBTi's verified approaches are described in the following. SBTi is a collaboration between i.a. CDP, United Nations Global Compact and World Wide Fund for Nature (WWF) (SBTi, 2019b). External monitoring whether a company achieved its verified target is thus directly based on emission reports to CDP. SBTi differentiates between three target-setting approaches: (1) Sectoral Decarbonisation Approach (SDA), (2) Absolute-Based Approach, (3) Economic-Based Approach (SBTi, 2018b). The aim of all approaches is to derive emission reduction pathways in line with a global 2 °C target based on the 2 °C scenario (2DS) compatible carbon budget calculated by IEA (2014).

The SDA distributes the overall 2 °C-carbon budget to different sectors and subsequently single companies. The approach was described by Krabbe et al. (2015) and is summarised in the following. SDA takes into account a company's initial performance and its projected activity growth until the target year. A sectoral emission pathway is transferred into a sectoral intensity pathway, i.e. the sectoral emissions pathway is divided by the forecasted average activity of the sector. In the SDA for uniform sectors such as the steel and automotive industry, activity projections are based on physical indicators such as p-km provided by sold vehicles. The sum of all company targets within a sector cannot overshoot the calculated sector carbon budget resp. emissions pathway. All companies' initial CO_2 intensity per activity (i.e. output) must converge to a general sector-specific intensity in 2050. According to the authors, using the SDA for target-setting within a 10-15 years timespan is more accurate than for longer timespans. Additionally, they claim that the SDA is most practicable for companies as differences in starting activities between companies are considered. As such, companies are granted time until a common carbon intensity must be met by 2050. SBTi requires OEMs to use the SDA tool to submit their targets (SBTi, 2019c). In this tool, International Energy Agency's Mobility Model (MoMo) indicates the future mobility demand as the basis to compute Paris Agreement-compatible carbon emission pathways for OEMs (WWF, 2019).

In the Absolute-Based Approach a globally valid percentage reduction of absolute emissions demanded by the 2°C-scenario (2DS) is transferred to all sectors and companies. To stay within a 2 °C carbon budget, companies are required to reduce absolute emissions between 2010 and 2050 by at least 49%, i.e. 1.23% annually (SBTi, 2018b). Krabbe et al. (2015) criticise this approach because differences between sectors regarding potentials for mitigation are not addressed. As neither starting nor projected carbon intensities are included, this approach does not necessarily lead to compliance with a global budget (Krabbe et al., 2015).

The Economic-Based Approach refers to economic data to set targets but is currently updated by the SBTi (SBTi, 2018b). The organisation indicates that economic-based reduction targets need to be in line with the physical output-based SDA above. Krabbe et al. (2015) describe an economic-based based variation of the SDA. Instead of indicating carbon intensities per physical indicator, economic indicators like value added are used. The value added is assumed to develop according to projected GDP growth to derive emissions intensity pathways. The authors recommend this approach to companies producing heterogeneous products such as the pharma industry. However, they conclude that mitigation potentials can more accurately be related to physical indicators than economic ones.

2.2.4 Summary

The guiding sub-research question of chapter 2.2 is: “what are existing carbon management approaches of OEMs?”. The analysis above shows that corporate carbon management is a broad field which is distinguished in carbon accounting and carbon controlling. Corporate carbon accounting comprises all activities related to gathering carbon-related information on direct and indirect GHG emissions. Carbon accounting follows widely accepted standards based on the GHG Protocol. The majority of companies worldwide publicly report their emissions to CDP. Based on the information provided by VW AG, BMW AG and Daimler AG, OEMs’ scope of reported emissions and calculation approaches are similar. Whereas scope 1-2 emissions are directly sourced from environmental information systems, vehicle LCA studies provide the basis for extrapolating material supply chain and EoL emissions to company level. Over 70% of OEMs’ absolute emissions are caused during vehicles’ use phase. Based on reported fleet tailpipe emissions to legislating institutions, TTW emissions are estimated based on an assumed 150,000-200,000 lifetime kilometrage. WTT emissions are mainly calculated separately for each market.

Corporate carbon controlling is defined as comprising all activities related to strategic decision-making concerning the future reduction of direct and indirect GHG emissions. It thus involves future emissions modelling and assessment of effective reduction measures. Though there are theoretical frameworks and general recommendations for establishing a carbon controlling system, practical tools for OEMs are, to the author’s knowledge, non-existent. Recommendations for the development of carbon controlling approaches include (a) basing it on the scope of past emissions reporting, (b) taking into account sector-specific requirements, (c) making modelling approaches compatible with past emission reporting systems to minimise data collection efforts and facilitate monitoring the progress of operationalised reduction measures. Last, developing a KPI to track the reduction progress towards a set target is recommended.

Setting reduction targets as a part of corporate carbon management is outsourced to external institutions in this study. As the goal of this dissertation is to develop a method serving as decision-support on most effective reduction measures towards reaching a Paris Agreement-compatible target, the level of necessary absolute reduction in emissions is determined by using external support. SBTi provides three target-setting approaches but requires OEMs to use their Sectoral Decarbonisation Approach (SDA) tool to submit their targets. Emissions reduction pathways derived from either of the approaches are based on a Paris Agreement-compatible carbon budget.

2.3 OEMs' future emissions: influencing factors

The analysis of reported carbon emissions of OEMs above shows that emissions caused by raw material extraction and processing, in-house production, usage and EoL treatment cover over 90% of absolute emissions. These core emission sources are focused on in the following analysis. *Sub-research question 2* ("Which factors influence future absolute emissions of OEMs?") is addressed. Emissions sources depend on external as well as internal factors. The development of external factors cannot directly be influenced by OEMs and include legal issues such as legislations on emission thresholds and societal developments such as type and magnitude of mobility demand. Internal factors are directly controlled by OEMs and include decisions taken on product level such as type of vehicles produced and on fleet level such as powertrain mixes and choice of markets. Although some internal factors depend on external factors like powertrain mixes of fleets depending on tailpipe emissions legislations, I distinguish between the two to highlight the complexity of parameters influencing future carbon emissions of OEMs. I will first describe external factors and exemplarily predicted developments until 2050 followed by internal factors and a respective range of options that can be pursued to reduce absolute carbon emissions.

2.3.1 External factors

Legislations

Over the life cycle of Internal Combustion Engine (ICE) LDVs over 70% of CO_2 emissions occur during the use phase (Danilecki et al., 2017). Hence, market-specific tailpipe emissions regulations aim at reducing the share of ICEs in OEMs' fleets. Until 2025, fleet emissions will be lowered from currently 120 to 81 g CO_2/km in the EU, from 154 to 97 g CO_2/km in the US and from 161 to 117 g CO_2/km in China (European Parliament, 2018a; ICCT, 2017). Therefore, OEMs must produce more fuel-efficient ICEs and alternative powertrains such as Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) to meet the requirements. As fully electrified vehicles do not cause TTW emissions, increasing shares of BEVs in OEMs' fleets will impact scope 3 cat. 11 emissions.

CO_2 intensity of electricity mixes

With rising shares of BEVs, scope 3 cat. 11 emissions will increasingly depend on CO_2 intensities of electricity mixes. Although BEVs do not cause TTW emissions they can cause high WTT emissions depending on electricity mixes used to charge the battery (Egede et al., 2015; Hawkins et al., 2013; Helms et al., 2016). Current CO_2-intensities of electricity mixes vary between markets and countries. According to the LCA software GaBi v8.7 SP36 (thinkstep) 2018 CO_2 intensities are 0.417 kg CO2/kWh in the EU, 0.614 kg CO2/kWh in the US and 0.867 kg CO2/kWh in China (CN) (thinkstep, 2018). According to IEA (2017a), the current global average of carbon intensity in electricity mixes is 520 grams of CO_2 per kWh (g CO_2/kWh). If all parties stick to their Nationally Determined Contributions for the Paris Agreement, the average carbon intensity has to be reduced to 254 g CO_2/kWh by 2060. However, according to the report, to achieve a below-2 °C target, CO_2 intensity of electricity production must fall to -10 g CO_2/kWh to support offsetting of residual carbon emissions of the transport sector. With rising shares of BEVs in the global LDV fleet predicted until 2060 (IEA, 2017a), the development of electricity mixes represents a crucial external factor influencing future absolute carbon emissions of OEMs. For example, the difference of life-cycle CO_2 emissions of the electrified Mercedes-Benz GLC running on the EU electricity mix versus running on electricity from hydropower is 12.3 t CO_2 (Daimler, 2018b). When extrapolating this effect to continuously electrified fleet levels, the impact on OEMs' absolute emissions will be noticeable. For example, according to PwC (2017), in 2030 55% of newly registered vehicles in Europe will be BEVs. Likewise, the production of Lithium Ion Batteries (LIB) and especially the battery cell production is energy-intensive (Romare and Dahllöf, 2017). Hawkins et al. (2013) state that LIB production is accountable for 15-19% of an electrical vehicle's life-cycle carbon emissions depending on the type of LIB used. Therefore, the CO_2-intensity of electricity mixes used to produce LIBs also has an impact on supply chain emissions (cat. 1).

Mobility demand
Although fleet emissions standards were lowered between 2014 and 2017 by 10% in the EU and US and by 14% in China (ICCT, 2017), absolute carbon emissions reported to CDP by the three top-selling OEMs VW, Toyota Motor Corporation and Renault Nissan increased in the same timespan (CDP, 2018a). The main reason for this development is rising vehicle sales. For example, VW's reported carbon emissions rose by 3% and vehicles sales rose by 5% between 2014 and 2017 (VW, 2015, 2018a). Rising vehicle sales can be attributed to growing mobility demand (Schäfer and Victor, 2000). At this point, the difference between "mobility" and "traffic" matters. Litman (2011) defines "traffic" as movement of vehicles generating vehicle-kilometres (v-km) and "mobility" as movement of people or goods generating person-kilometres (p-km) or tonne-kilometres (t-km). Here, mobility demand refers to passenger LDV traffic volume being converted to p-km. Via average load factors, i.e. the number of passengers transported per vehicle-kilometre (p/v-km) and annual v-km of LDVs, the number of demanded vehicles per year can be calculated (Schäfer, 1998).

The consultancy Pricewaterhouse Coopers (PwC) projects growing mobility demands in the EU, US and China (PwC, 2017). Between 2017 and 2030 the authors project a 23% increase of mobility demand in the EU (2% p.a.), a 24% increase in the US (2% p.a.) and a very pronounced 183% increase in China (14% p.a.). The International Transport Forum (ITF) and the OECD project a slower increase in mobility demand. Between 2015 and 2050 private urban mobility demand in OECD countries will rise by 33% (1% p.a.) and by 157% in non-OECD countries (4% p.a.) markedly in Asia (OECD/ITF, 2017). When interpolating computed motorised mobility demands by Schäfer and Victor (2000) the projections for the Western Europe and the North American region are similar to (PwC, 2018). The authors predict a 28% increase of mobility demand in WES and a 24% increase in NAM between 2017 and 2030. However, the projection for Centrally Planned Asia (which includes China) is markedly lower with only 84% increase of mobility demand. Although these three sources differ in their projection of mobility demand developments, they show three clear trends: (1) overall mobility demand is increasing, (2) the highest increase is expected in Asia, (3) EU and US mobility demands will develop similarly.

Although IEA (2017a) do not make their predictions concerning the development of mobility demand in p-km publicly available, they expect an increase of +105% for global LDV sales between 2015 and 2060.

In order to decrease absolute emissions of OEMs while increasing sales, life-cycle carbon emissions per vehicle must be lowered even further than with stagnating sales. If an OEM decides on reducing absolute CO_2 emissions by -50% between 2015 and 2025, respective relative CO_2 emissions per vehicle depend on projected vehicle sales in this timespan. If sales are expected to increase by 25% between 2015 and 2025, relative CO_2 emissions must decrease by 60% until 2025 to meet the absolute reduction target.

Mobility services
The rising mobility demand will be met with private vehicles and mobility services alike. Private vehicles are distinguished from mobility services as these are bought by a costumer whereas mobility service vehicles remain property of the provider. In general, the terms "mobility service" or "Mobility as a service (MaaS)" refer to digitally connected transport services (Hensher, 2017). Therefore, a requirement for providing mobility services efficiently are cloud-based applications connecting customers and mobility service vehicles (McKinsey&Company, 2019). Mobility services are offered by firms, public bodies or private persons to customers in exchange for money (Hensher, 2017). Mobility services are likely to replace private vehicles in the future (Bellos et al., 2017; Chen and Kockelman, 2016).

PwC (2017) predict shares of mobility services on overall mobility demand of 25% in Europe, 33.5% in the US and 45% in China by 2030. Both McKinsey&Company (2019) and PwC (2017) refer to the ACES trends shaping future business models of OEMs (Figure 12). ACES stands for Autonomous Driving, Connectivity, Shared Mobility and Electrification. These four trends are supposed to be reinforcing each other. Autonomous vehicles are expected to boost the demand for mobility services as these will be cheaper for both providers and customers once drivers' salaries become obsolete (PwC, 2017). Due to e.g. stricter fleet emission standards and customers demanding use phase emission-free vehicles, mobility services are projected to rely on electrified powertrains. This includes customers seeking vehicles powered with energy from renewable sources (PwC, 2017).

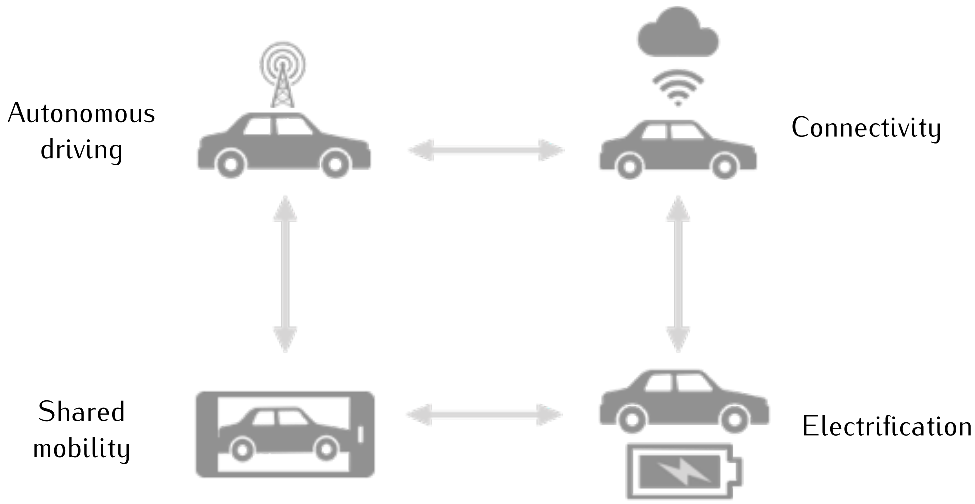
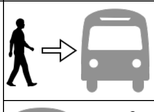
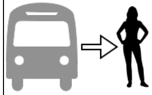


Figure 12 ACES trend based on McKinsey&Company (2019). The four trends are expected to reinforce each other.

Categorising mobility services

Use patterns of private vehicles and mobility services differ. Customer-owned vehicles are on average used for one hour per day whereas the daily timespan in which service vehicles are used is prolonged as several people have access to one vehicle (UBA, 2017). Characteristics of different four-wheeled mobility services can be further distinguished (Table 5): for individual mobility services, one passenger or group of associated people define time and locality of the service's start and end point. For shared mobility services, several un-associated passengers who travel along a similar route define the service's start and endpoint. The services can be further differentiated by their direction of service. Either the customers pick up and drive the vehicle themselves or the customers are being picked up by a driver or, in the future, an autonomously driving vehicle. A full automation of car sharing and leasing vehicles is likewise possible. However, an autonomous car sharing vehicle would be ordered online to pick up the customer which, in fact, turns it into ride hailing service. The same holds true for leased vehicles. In this case, a fully automated vehicle would be used by one contemporary renter only. This development is deemed unlikely as a full automation of vehicles is predicted to be accompanied by shared mobility concepts and connectivity. Although electrification in combination with rising shares of mobility services is predicted, current service vehicles represent the whole range of market-ready powertrains.

Table 5 Characteristics of four-wheeled mobility services based on Neef et al. (2019).

	Service direction	Individual	Shared	Autonomous vehicles	Powertrains
Type of mobility service		Car sharing Car leasing		Possible (not likely)	All (ICE, PHEV, BEV, FCEV, Ethanol, CNG)
		Ride hailing/ Ride sourcing	Ride pooling	Possible (likely)	

Examples for individual mobility services are car sharing and leasing as well as ride hailing. Car sharing customers have access to a vehicle fleet by paying a membership fee and additional fee based on the respective amounts of kilometres driven (Martin and Shaheen, 2011). In contrast to car leasing, a car sharing vehicle can be used by several customers. Leased vehicles are used by only one customer during the leasing timespan. Therefore, use patterns of leased and customer-owned vehicles do not differ (Nurhadi et al., 2017). Ride hailing (sometimes referred to as "ride sourcing") is comparable to ordering a taxi. Customers order a vehicle via an app by indicating their start and endpoints and are picked up at the respective location. The service direction of ride hailing is thus reverse to that of car sharing and leasing.

An example for a shared mobility service is ride pooling. Customers order the service via app and are picked up at the indicated location. Based on algorithms and the similarity of customers' journeys the service provider calculates which vehicle "pools" which customers for a certain trip.

The main difference between these mobility services is the average load factor (lf). The load factor indicates the average amount of persons per vehicle-km (v-km). Depending on the total v-km a vehicle is being driven over its lifetime ($tVKM$) and lf, a vehicle's total amount of provided person-km (p-km) can be calculated ($tPKM$). In case of pick-up services provided by ride hailing and pooling the "empty travel rate" (et) needs to be taken into account. "Empty travels" describe vehicles consuming fuel or electricity without transporting customers, i.e. v-km are being driven while no p-km are being provided. Fagnant and Kockelman (2014) computed a 10% share of empty travels on total vehicle kilometrage for autonomous ride hailing vehicles. The 10% empty travel rate is likely to be similar for non-autonomous ride hailing and pooling services as these face the same "relocation problem". The lifetime person kilometrage of a vehicle is calculated as follows:

$$\text{tPKM} = (tVKM * lf) - et$$

(2.1)

Assuming a fixed $tVKM$, a vehicle can provide a range of tPKM based on its respective lf. Vehicles with higher lf thus offer a higher number of lifetime p-km and thus a higher share of the mobility demand than private vehicles. As a result, with higher lf fewer vehicles are needed at a certain point in time.

Load factors, renewal & replacement rates

According to the European Environment Agency (2008), the average load factor of private vehicles in the EU in 2008 was 1.45 persons/v-km. The latest data that could be obtained for the US is 1.59 persons/v-km in 2009 (Office of Energy Efficiency & Renewable Energy, 2010). As no empirically collected data is available for China, Huo et al. (2012) estimate an average load factor of 1.5 persons/v-km for private vehicles. As pointed out above, leased vehicles have the same average load factors as private vehicles.

Car sharing vehicles have a similar average load factors as private vehicles as they are driven by the customers themselves. Nijland and van Meerkerk (2017) state an empirically collected load factor of 1.39 for car sharing vehicles. However, as customers drive the vehicles themselves to use them "as their own" the load factor of car sharing vehicles can be assumed to be similar resp. the same as those of private vehicles. The difference to private vehicles lays in the capacity utilisation. Car sharing vehicles are used more frequently as numerous customers use the same vehicle at different times. Therefore, car sharing vehicles' lifetime vehicle kilometrage is provided in a shorter timespan than private vehicles' lifetime kilometrage. Thus, the use phase is temporally shorter while the same number of p-km is provided. Since more people can satisfy their personal mobility demand with a single vehicle, fewer vehicles are needed at a certain point in time. I.e. with higher shares of car sharing vehicles serving the overall mobility demand e.g. less parking space would be needed. Likewise, PwC (2018) state that increasing shares of mobility services like car sharing will lower the functional vehicle stock. However, the authors claim, this development will also have positive impacts on new vehicle registrations and thus the production of vehicles. This is due to the higher capacity utilisation of shared vehicles and hence faster renewal rates of fleets.

Another important aspect of car sharing and its impact on the number of privately owned vehicles are replacement rates, i.e. the ratio of one car sharing vehicle replacing a certain amount of private vehicles among the programs' members. Thus, reducing the overall number of vehicles in a defined area. Customers and city planners therefore often perceive the reduced number of vehicles on the streets as a positive effect of car sharing. However, this approach does not include assessing the overall number of vehicles that have to be produced per year to offer a certain mobility demand as it does not include faster renewal rates of car sharing vehicles compared to private vehicles due to higher capacity utilisation. The approach aims at showing the impact of car sharing on the number of vehicles on the streets at a certain point in time. It is thus not helpful to assess car sharing's impact on OEM fleet sizes. Still, the range of replacement rates provided in the literature and their validity are assessed below.

For example, Baptista et al. (2014) use a replacement factor of one car sharing vehicle replacing six private vehicles based on a survey among car sharing customers in Lisbon, Portugal. However, only 4% of interviewees stated the "desire to stop owning a private vehicle" (p. 34) and none indicated to have replaced their private vehicle yet. Chen and Kockelman (2016) report a range of nine to 23 replaced private vehicles in the U.S.. These values are based on several other studies in which replacement rates were estimated. The German Environmental Ministry (UBA) states a replacement rate of one car sharing vehicle replacing 15 private vehicles based on an overview of different surveys conducted by the national car sharing organisation (bcs) (UBA, 2017). In the German surveys, up to 20% of customers stated to have replaced their private vehicle by the use of car sharing. These replacements include both not buying a new vehicle after scrapping the old one and selling still functional vehicles. In how far car sharing customers replaced their private vehicles differed among station-based and free-floating car sharing customers. Station-based car sharing customers replaced their vehicle on average more often than free-floating car sharing customers. In station-based car sharing programs vehicles are picked up and returned to the same fixed location. Free-floating car sharing programs are more flexible, i.e. customers check online where a free service vehicle is parked and can leave within a broader area. In a London study, up to 25% of car sharing customers replaced their private vehicle. In contrast to other studies, an analysis of other influencing parameters is provided. I.e. the authors assume that the introduction of an inner city toll for private vehicles influenced the decision-making process of replacing a private vehicle with car sharing (bcs, 2016). In their literature review on car sharing's impact on customers mobility behaviour Baptista et al. (2014) show that replacing private vehicles due to car sharing in the U.S and Europe is repeatedly accompanied with an increased use of other transport modes such as biking and public transport. It can therefore be assumed that not only the car sharing program itself but other parameters such as quality of public transport and biking infrastructure influence decisions on replacing a private vehicle or not. This hypothesis is backed by Firnkorn and Shaheen (2016) who state that it is challenging to establish causality between changing mobility behaviour and joining a car sharing program as a multitude of parameters (that are not necessarily inquired in questionnaires) like an illness or a new workplace influence personal mobility behaviour. Moreover, they highlight that mobility behaviour of car sharing customers can change over time, i.e. studies focusing on one point in time rather than a longer timespan might lead to wrong conclusions. For example, the authors state that during the first year of a San Francisco car sharing program customers' v-km actually increased compared to v-km before joining the program. However, during the second year, this trend was reversed and v-km was considerably lowered. In how far car sharing leads to private vehicles being replaced is thus highly contextual. More replicable empirical research on mobility behaviour of car sharing customers in different settings is therefore necessary.

Similarly, empirically collected data on mobility services' load factors is scarce (Firnkorn and Shaheen, 2016). Still, a ride hailing load factor in San Francisco of 1.8 persons/v-km was empirically evaluated by Shaheen et al. (2014). Ride hailing vehicles' average load factor (excluding the driver), is thus slightly higher than of individual vehicles. An empirically verified load factor for ride pooling vehicles could not be found. However, in a modelling experiment Santi et al. (2014) identified a load factor of 3 persons/v-km as achievable for ride pooling vehicles. The International Transport Forum (ITF) identified a load factor of up to 2.3 persons/v-km specifically for a six-seater ride pooling vehicle (ITF, 2018). A load factor higher than 4 person/v-km is not impossible to compute according to Santi et al. (2014). In the examples above, non-autonomous vehicles were assessed. Still, it can be assumed that load factors of fully automated ride hailing and pooling vehicles are similar to conventional vehicles: the driver of conventional service vehicles is not part of the indicated load factor and future (possibly autonomous) service vehicles' pick-up service will be based on algorithms as is the case already today. It is possible that load factors of ride hailing and pooling vehicles differ among markets as they do for individual vehicles. However, no market-specific load factors could be obtained from the available literature.

OEMs' current engagement in mobility services

OEMs are reacting to the servitization trend in the mobility sector and are integrating car sharing, ride hailing and ride pooling into their fleets (Firnkorn and Shaheen, 2016). For example, "mytaxi" by Daimler AG and "Gett" in which VW is invested represent ride hailing services (Daimler, 2020; VW, 2016a). Car sharing services offered by OEMs are, e.g., "DriveNow" by BMW AG and "Car2go" by Daimler AG (BMW, 2018b; Daimler, 2020). VW's "MOIA shuttle" is an example of an OEM providing a ride pooling service. Whether and in how far selling mobility services instead of private vehicles is impacting OEMs absolute carbon emissions is, however, not yet known (Firnkorn and Shaheen, 2016).

Rebound effect
A phenomenon that is repeatedly addressed within research on mobility services is the so-called rebound effect. In general, it describes the added energy consumption following modifications in demand structure due to behavioural changes resulting from increased energy efficiencies per unit. In the case of transportation, associated rebound effects are consumers buying heavier vehicles and driving longer distances due to improvements in fuel efficiency (Font Vivanco et al., 2016).

Concerning mobility services, Pakusch et al. (2018) and Clewlow and Shankar Mishra (2017) expect increasing shares of car sharing and ride hailing to result in a diminished use of public transport. I.e. the overall amount of v-km travelled in non-public vehicles is expected to increase. These findings are contrasting the surveys presented above which conclude a higher utilisation of public transport along with increased use of car sharing programs. Again, these diverging findings call for more empirical studies on the topic.

Ride hailing might also lead to trips that would have been avoided without readily available mobility services (Clewlow and Shankar Mishra, 2017). Another rebound effect resulting from the widespread introduction of mobility services might be that societal groups which are so far not heavily involved in individual motorised transportation like children, elderly people and people with medical conditions might boost the overall p-km demand (Harper et al., 2016). However, according to Clewlow and Shankar Mishra (2017), current users of ride hailing are mostly urban young high-income customers between 18 and 29 years. The question whether and in how far mobility services make individual transportation more carbon efficient should therefore be addressed including rebound effects, if possible.

Mobility services & LCA
Past-oriented carbon accounting approaches take on a life-cycle approach and mobility services are expected to play a major role in OEMs' future fleets. They are thus an important external factor influencing absolute emissions. Therefore, in order to address the main research question, it is necessary to analyse available approaches of assessing and comparing the carbon performance of mobility services and private vehicles from a life-cycle perspective. How are differences in p-km provision between private and service vehicles and data insecurity regarding rebound effects, load factors and replacement rates dealt with? Does autonomous driving have an impact on carbon performances? The answers to these questions are essential in order to develop the CBC method. For this reason, a standardised literature review is conducted in Chapter 2.4 addressing the additional **sub-research question 2a**: "*What are common characteristics of LCA-based approaches to assess and compare CO_2 performances of private and mobility service vehicles?*".

2.3.2 Internal factors

Company structure
Emissions can be highly diverse among OEMs' sub-brands. For example, OEMs like General Motors Company and VW own eight and nine brands, respectively, producing passenger vehicles (GM, 2018; VW, 2018b). Brands can differ in types of vehicles offered, markets they are active in and vehicle output. VW Group's SEAT sold over 90% of their LDVs in Europe in 2017 whereas AUDI sold less than 50% of their LDVs in Europe and 36% in the Asian-Pacific region (VW, 2017a). Additionally, sales numbers differ between brands: of BMW AG's total sales in 2017 Mini sold roughly 15% and BMW 85% (BMW, 2018c).
Even within one brand the portfolio can be highly diverse including models with higher and lower life-cycle carbon emissions. Daimler AG offers a Sport Utility Vehicle (SUV) causing 67.2 t CO_2 over its life cycle and A-Class vehicles causing less than half the amount of emissions (30.4 t CO_2) (Daimler, 2018e, 2018b).

Product specifications & battery technologies

OEMs' chosen vehicle specifications and subsequent scale-up to fleet levels is a decisive factor influencing absolute CO_2 emissions. LCA studies of LDVs analyse CO_2 hotspots of different powertrains and illustrate reduction potentials. As most OEMs are focusing on electrified vehicles to lower carbon emissions (see e.g. Daimler (2018f)), CO_2 hotspots and respective reduction potentials of ICEs and electrified vehicles are described below.

Increasing weight is positively correlated with increasing carbon emissions in the manufacturing stage of vehicles of all powertrains as more raw material need to be extracted and processed. As SUV sales are globally increasing (Carey, 2018; Tabuchi, 2018), OEMs' absolute CO_2 emissions are bound to increase as well. BEVs' increasing vehicle weight is due to embedded LIBs. Regarding currently available battery technologies, growing LIB size is positively correlated with a higher CO_2 footprint of its production (Romare and Dahllöf, 2017). Included battery technologies used in current BEV and PHEV models are mostly manufactured from a cathode made from lithium or iron phosphate with a mix of manganese oxides, nickel and cobalt and an anode mainly based on graphite. The respective abbreviations used in this context are i.a. NMC (Lithium manganese cobalt oxide), NCA (Lithium nickel cobalt aluminum oxide) and LFP (Lithium iron phosphate) (Romare and Dahllöf, 2017).

For the production of these battery cells (excluding the raw material supply chain) the authors provide an energy intensity range of 350-650 MJ/kWh battery capacity, i.e. a mean value of 500 MJ/kWh. This energy use is mainly due to electricity consumption and not further specified. Therefore, the carbon intensity of battery production is highly dependent on the carbon intensity of the used electricity source (Romare and Dahllöf, 2017). The carbon intensity of LIB production can be lowered by using renewable energy during battery cell manufacturing. According to Ellingsen et al. (2014) in the case of an NCM battery, an overall carbon intensity of 172 kg CO_2-equivalents/kWh can be reduced by 60% when using hydropower instead of a mainly coal-based electricity mix (46% coal, 15% nuclear, 15% gas). For this technology every battery cell is based on a cathode out of $Li(Ni_xCO_yMn_z)O_2$ and an anode manufactured from graphite. Making sure that LIB suppliers use renewable energy could thus lower absolute CO_2 emissions of OEMs.

Future LIB technologies like solid state batteries with solid electrolytes are likely to increase energy capacities while lowering the weight of the batteries (Romare and Dahllöf, 2017). However, publicly available information on specific CO_2 emissions arising from manufacturing solid state batteries could not be found. Additionally, the German thinktank Agora Verkehrswende states a future general CO_2 reduction potential in LIB production due to higher utilisation of plants and more CO_2-efficient energy mixes as well as due to a change in technology from 1:1:1 NMC battery cells to 6:2:2 NMC battery cells (Agora Verkehrswende, 2019).

Mining of rare materials contained in current LIBs like cobalt and nickel only causes a small share of carbon emissions on total emissions associated with LIB production. Kelly et al. (2019) indicate roughly 11 kg CO_2/kWh LIB caused by the extracting and processing of nickel and cobalt. I.e. 15% of overall CO_2 emission caused during LIB production.

Still, recycling of materials offers further CO_2 reduction potentials and economic savings (Romare and Dahllöf, 2017; Zheng et al., 2018). In Romare and Dahllöf (2017), Buchert et al. (2011a) are cited with a 1035 g CO_2-e/kg battery reduction potential in a hydrometallurgical approach and Buchert et al. (2011b) with a 1244 g CO_2-e/kg battery reduction potential in a pyrometallurgical approach. Though in the pyrometallurgical approach only cobalt, nickel and copper can be extracted and need to be further refined for re-use in LIB manufacturing. Included battery technologies are NMC, LFP, NCA (Romare and Dahllöf, 2017). Zheng et al. (2018) state a potential 2.5 billion spent LIBs in China by 2020 underlining the potential CO_2 savings from using recycled LIB materials in the future. However, at this point it is difficult to estimate the amount of recycled materials re-used in automobile LIBs at a certain point in time and thus the specific carbon-saving potential per kWh LIB. Another possibility is that used LIBs be put to secondary use by serving as modular energy storage units in residential areas (Reid and Julve, 2016). Though Romare and Dahllöf (2017), do not predict a sizeable "second life market" for LIBs in the near future. As ICE's tailpipe emissions are directly controlled by emissions legislations, I focus on carbon reduction potentials of BEVs. BEVs remain, until now, untouched by emission legislations as no TTW emission are caused. However, life-cycle emission regulations are being discussed in the European Parliament (European Parliament, 2018b) which would draw attention to carbon hotspots of electrified vehicles. Such an approach has also been proposed by Lehmann et al. (2015). I classify the CO_2 intensity of electricity mixes as external factors. Nevertheless, OEMs started making energy supply chains an internal factor. For example, BMW AG and Daimler AG are cooperating with energy providers to sell renewable energy contracts to BEV owners in Germany (BMW, 2018d; Daimler, 2015). According to Institut für Energie- und Umweltforschung (Ifeu), using 100 percent renewable energy during the use phase of BEVs can lower life cycle carbon emissions per vehicle by ca. 67 percent compared to the 2015 German electricity mix (Ifeu, 2015).

Production
OEMs have direct control over the energy sources used on their production sites. Reducing emissions is possible with energy-efficiency measures or by switching to renewable energy sources. Similar to energy-intensive processes like usage of BEVs and LIB production, OEMs can either rely on regional electricity mixes or negotiate renewable energy contracts with electricity providers like e.g. Daimler AG (Daimler, 2018f). Additionally, OEMs modify their own power stations to save CO_2 emissions. VW is rebuilding its Wolfsburg power plant to use natural gas instead of coal to reduce associated emissions (dpa, 2018). VW aims at reducing scope 1 and 2 emissions by 45% between 2010 and 2025 and Daimler AG aims at running its German plants with zero scope 1 and 2 emissions by 2022 (CDP, 2018a; VW, 2018a).

2.3.3 Summary

Chapter 2.3 aims at answering sub-research question 2 ("What is influencing future absolute emissions of OEMs?"). OEMs' emission drivers can be distinguished in external and internal influencing factors. External factors cannot directly be controlled by OEMs as they depend on political and societal developments. A crucial external factor is tightening tailpipe emissions legislations. OEMs aim at meeting stricter emissions legislations with increasing shares of BEVs in their fleets. However, the life-cycle carbon performance of electrified vehicles is dependent on the CO_2-intensity of electricity mixes used during energy-intensive LIB production and vehicles' use phase. The share of low-carbon energy sources in electricity mixes will therefore have an immense impact on OEMs' future emissions. The number of vehicles produced per year is the main driver of OEMs emissions. Future mobility demand is expected to increase until 2050, especially in Asia. OEMs will thus have to increase their CO_2 reduction efforts per vehicle to counteract rising sales. Though future mobility demand will not only be served by selling private vehicles but also by offering mobility services. Mobility services like ride hailing and ride pooling are assumed to have higher average load factors than private vehicles. Therefore, less mobility service vehicles are needed to satisfy the same mobility demand compared to private vehicles. However, empty travels of ride hailing and pooling as well as possible rebound effects of readily available and affordable mobility services should be considered. How far different types of mobility services will be demanded by customers and in what way these will reduce the number of annually produced vehicles will thus impact OEMs future carbon performance.

Internal influencing factors are directly controlled by the OEM. Types of brands owned by an OEM with respective vehicle models influence absolute emissions. Premium brands offering larger vehicles with higher motorisation rates also cause higher carbon emissions per vehicle. Likewise, selling increasing numbers of SUVs raises OEMs' absolute emissions. I.e. not only the amount but also the type of vehicle produced and used has an impact. Furthermore, OEMs can actively intervene in their supply chain and in-house production processes. Carbon hotspots in the supply chain such as LIB production can be tackled by making sure that renewable energy sources are used during manufacturing. Finally, emissions caused directly and indirectly on OEMs' own production sites can be cut by switching to renewable energy sources and reducing energy consumption.

2.4 Standardised literature review: LCA for comparison of mobility services' and private vehicles' life cycle carbon performances

Analysing existing LCA-based approaches to compare life-cycle CO_2 performances of private and mobility service vehicles is necessary to develop the CBC method (see 2.3). The obligatory steps for conducting an LCA study (Figure 3) are the same for assessing the environmental performance of services and products (Kjaer et al., 2016). The structure and general methodological requirements for LCA studies on private and service vehicles are thus the same. In contrast to private vehicles, mobility services are designated „product service systems“ (PSS). And, more specifically, as "use-oriented PSS" because the service vehicles are owned by the provider (Tukker, 2004). The following standardised literature review addresses this additional sub-research question:

Sub-research question 2a
What are common characteristics of LCA-based approaches to assess and compare CO_2 performances of private and mobility service vehicles?

Below, the methodology and the results of the review are described. The results will be discussed as part of the overarching chapter 2 deficit analysis (2.5). The subsequent development of CBC method will include the results obtained from this analysis. A shortened version of the literature review was published in Neef et al., (2019).

2.4.1 Methodology

In a first screening of the peer-reviewed literature, no review article on comparing life-cycle CO_2 performances of mobility services and private passenger vehicles could be found. This literature review aims at closing this research gap. In a standardised literature review a prior defined structure is followed to produce replicable results (Littell et al., 2008). Based on an approach introduced by Stechemesser and Guenther (2012) which includes merging structural proposals by Tranfield et al. (2003) and Fink (2010), the working steps are identified. First, search terms and to-be-screened databanks are decided on. Next, screening criteria and inclusion as well as exclusion criteria are defined. Finally, a review protocol is specified.

Review-guiding questions, search terms and databanks
Sub-research research question 2a is further specified to structure the review. Possible answers are pre-defined in categories to facilitate the evaluation (Table 6).

Table 6 Overview of review-guiding questions with respective categories.

Review-guiding questions		Pre-defined categories of characteristics
a)	What is the publication type?	Methodological/survey/case study
b)	Which mobility services are included?	(non-)/autonomous car sharing/car leasing/ride hailing/ride pooling
c)	Which powertrains are included?	ICE/(P)HEV/BEV/CNG/Ethanol/Biogas
d)	Which geographical scope is covered?	Urban region/rural region/national
e)	Which temporal scope is covered?	<1 year/1 year/vehicle lifetime
f)	Who is the audience?	customers/policy-makers/private sector/academia
g)	Which life cycle phases are covered?	production + use + EoL/combination of phases
h)	Which reference units are used?	v-km/p-km/v-km + p-km
i)	Which LCA approach is pursued?	accounting/consequential/mix of elements
j)	What challenges are mentioned?	n.a.

Databanks chosen to be used are Elsevier, Scopus and Web of Science. The following search term was applied to screen keyword, abstract and title of publications: accounting OR LCA OR „life cycle assessment“ AND CO2 OR carbon OR GHG OR „greenhouse gas“ AND „mobility service“ OR „car sharing“ OR PSS OR „product service system“.

Criteria

Case studies as well as review articles written in English are included in the screening process without putting restrictions on the publishing date. Higher and lower ranked journals are treated equally. By applying the search term, publications are, in a first step, screened by title and abstract. Based on sub-research question 2a, inclusion criteria 1 was applied to the publications which passed the primary screening (Table 7). Though this criteria led to only a small number of adequate papers. Therefore, inclusion criteria 2 was formulated as during the use phase, the highest share of CO_2 emissions of ICE-powered vehicles is caused (Danilecki et al., 2017). Moreover, the differences between products and PSS are most pronounced in the use phase as load factors can differ.

Table 7 Inclusion criteria

Inclusion criteria 1	The study follows a quantitative LCA-based approach for estimating CO_2 emissions of private and mobility service vehicles over the life cycle.
Inclusion criteria 2	The study comprises a quantitative approach for at least the use phase of private and mobility service vehicles.

The exclusion criteria (Table 8) are based on Annarelli et al. (2016). As this review is focusing on quantitative environmental performances (more specifically: carbon performances) of mobility service and private vehicles, design and economic research is excluded.

Table 8 Exclusion criteria

Exclusion criteria 1	The study assesses the design of mobility service vehicles.
Exclusion criteria 2	The study assesses possible economic gains of mobility service vehicles.

Review protocol

Similar to Stechemesser & Guenther (2012), a review protocol was used to organize metadata as well as methodological findings and results of every assessed publication. The protocol is structured around the review-guiding questions presented above. See Table 9 for an exemplary entry.

Table 9 Exemplary review protocol entry

Meta data		
Authors		Nurhadi et al.
Year		2016
Title		Competitiveness and sustainability effects of cars and their business models in Swedish small town regions
Name of journal		Journal of Cleaner Production
Type of publication	Which is the publication type?	Case study
Characteristics of assessed mobility service(s)		
Mobility service	Which mobility services are included?	Car sharing, car leasing, ride hailing
Powertrain	Which powertrains are included?	Biogas, ethanol, gasoline, PHEV, BEV
Methodological characteristics		
Geographic scope	Which geographical scope is covered?	City: Karlskrona, Sweden
Time horizon	Which temporal scope is covered?	1 year with different scenarios
Audience	Who is the audience?	Policy-makers
Life cycle scope	Which life cycle phases are covered?	Manufacture, use, EoL
Reference unit	Which reference units are used?	p-km
Load factors and v-km	How many p-km are driven with the mobility service?	3500 p-km/yr, 5 individuals/car/yr, i.e. 17500 p-km/yr, 9 yrs lifetime
Type of LCA	Which LCA approach is pursued? Are rebound effects included?	attributional
Challenges	What challenges are mentioned?	n.a.

2.4.2 Results

By applying the search term in the chosen databases, 848 publications were yielded. 32 duplicates were removed so that title, keywords and abstract of 816 publications were evaluated. This resulted in 766 papers being excluded. The full texts of 50 remaining publications were evaluated by referring to inclusion and exclusion criteria. As proposed by Randolph (2009), additional forward and backward searches of the remaining publications' references was performed. As such, three additional relevant papers were found. The work flow described above is shown in Figure 13.

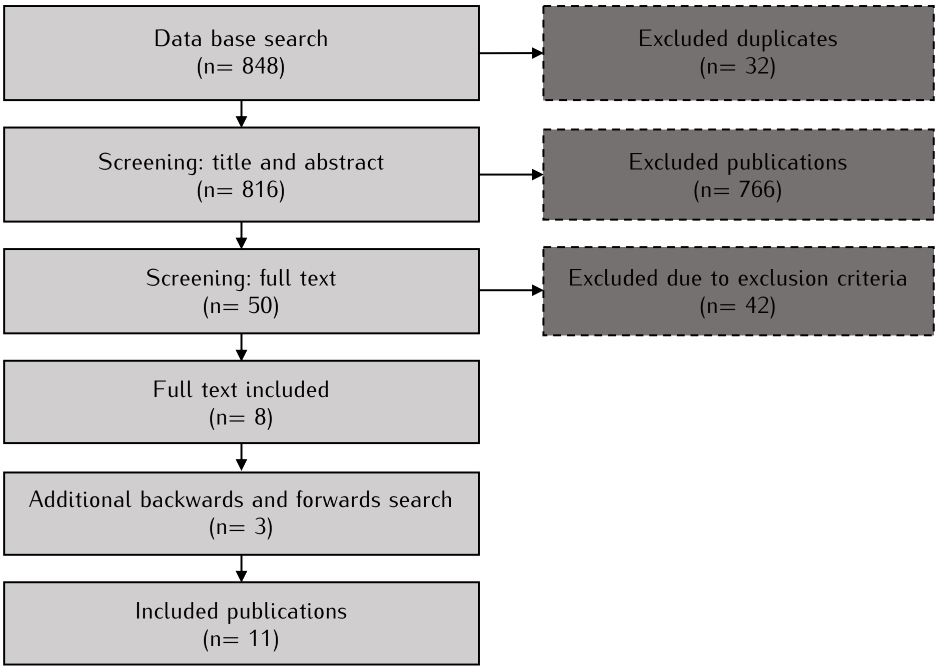


Figure 13 Workflow of literature review with quantitative results (based on Moher et al. (2009))

The review protocol's structure is used to facilitate the analysis in the following.

Meta data
The included 11 publications were published between 2005-2017 in mostly peer-reviewed journals. Two publications of university institutes are evaluated (see e.g. Briceno et al. (2005)). Five of the papers were published in 2016 or later. Nine publications represent case studies, one methodological publication is included (see Fagnant and Kockelman (2014)) and one review paper on accounting methodologies of several PSS is included (see Kjaer et al. (2016)).

Characteristics of mobility services
91% of publications include car sharing as one assessed mobility service (Figure 14). Fagnant and Kockelman (2014) evaluate shared autonomous vehicles (SAVs). This service is categorised as autonomous ride hailing. Car leasing and ride hailing are only assessed by Nurhadi et al. (2017) and Retamal (2017). In 91% of publications the authors evaluate ICEs (Figure 15). Additional PHEVs are included in 28% of publications and 18% assess solely BEVs. Nurhadi et al. (2017) also include ethanol- and CNG-powered vehicles. Kjaer et al. (2016) provide a review article so that no specific case study is provided.

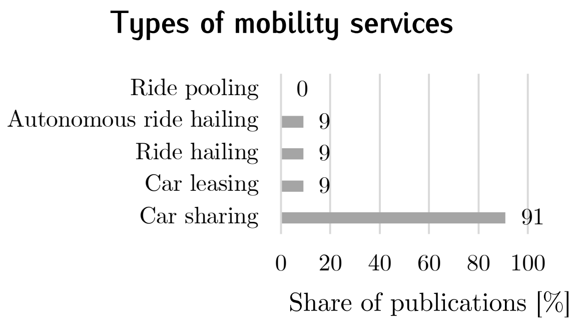


Figure 14 Mobility services included in the analysed studies. Numbers do not add up to 100% as several mobility services are analysed in one publication.

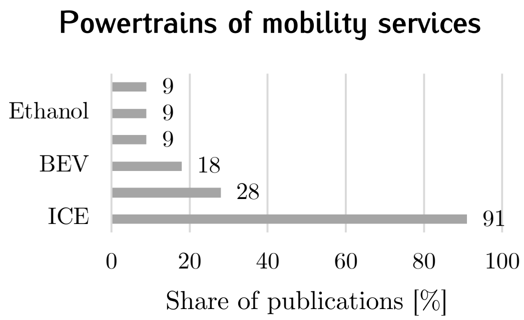


Figure 15 Powertrains of mobility service fleets. Numbers do not add up to 100 as several powertrains are analysed in one publication.

Methodological characteristics

Geographic scopes covered in case studies are mostly a specific city (36%) (see e.g. Namazu and Dowlatabadi (2015)), an urban area (see e.g. Chen and Kockelman (2016)) or a country (see e.g. Nijland and van Meerkerk (2017)) (Figure 16). Nurhadi et al. (2017) evaluate mobility services in a rural region. Figure 17 summarise the temporal scopes covered. One year is the dominating reference time horizon covered (55%). Fagnant and Kockelman (2014) use 100 days as a time frame, Mitropoulos and Prevedouros (2014) a vehicle's lifetime mileage of 119,780 miles and Chen and Kockelman (2016) an unspecified vehicle's lifetime. Retamal (2017) and Kjaer et al. (2016) do not apply defined temporal scopes. In the "audience" category, double-counting was possible as several publications addressed more than one audience type. The audience type "academia" was chosen for methodological publications. See Figure 18 for a summary of addressed audiences. Policy-makers are addressees of 82% of papers. Customers are addressed in 64% of papers and the private sector in 45%. Kjaer et al. (2016) address academia only.

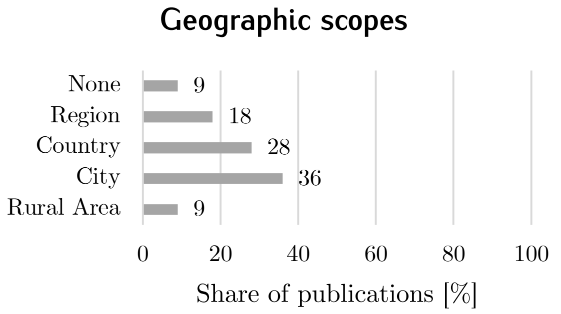


Figure 16 Geographic scopes covered.

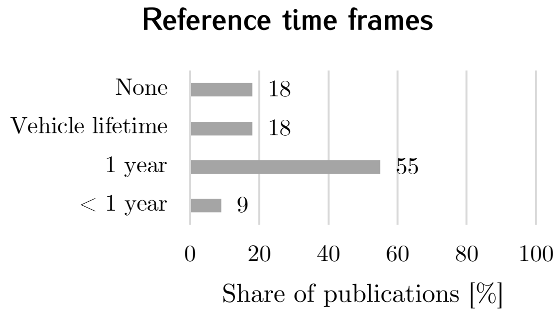


Figure 17 Reference timeframes analysed.

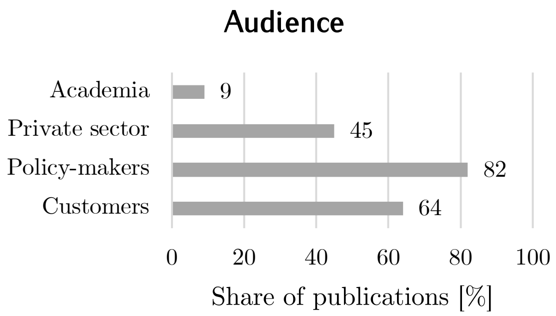


Figure 18 Audience categories of studies. Numbers do not add up to 100 as several audiences can apply to one publication.

64% of the yielded publications assess the whole life cycle of mobility service vehicles in their analyses (Figure 19). 28% account for use phase CO_2 emissions only (see e.g. Martin and Shaheen (2011)) and one paper focuses on both manufacturing and use phases (see Fagnant and Kockelman, 2014). Figure 20 summarises applied reference units. 64% of authors choose p-km as reference. 28% evaluate CO_2 performances of mobility service and private vehicles in v-km, 9% apply a combination of v-km and p-km. Kjaer et al. (2016) state that the functional unit of LCA studies should generally address the function offered by the assessed product or service. For mobility services this statement aims at evaluating results in p-km to take into account load factors of different modes of mobility.

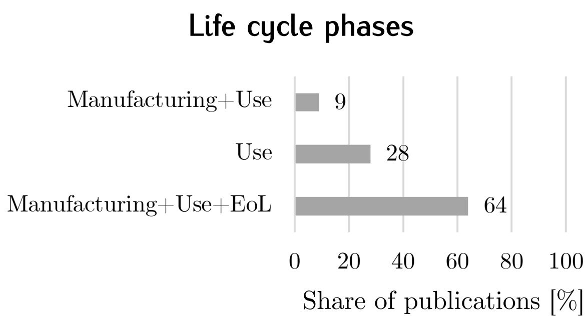


Figure 19 Life-cycle phases analysed in the studies. Due to rounding errors numbers do not add up to 100.

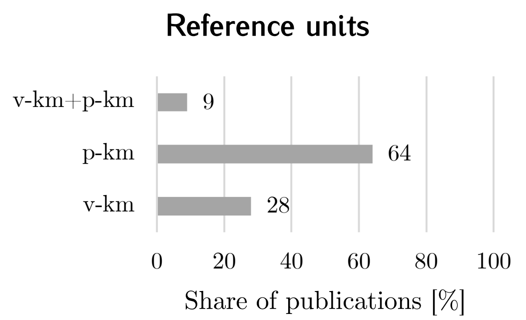


Figure 20 Reference units used for carbon performance measurements. Due to rounding errors numbers do not add up to 100.

Stated load factors of vehicles used in car sharing strongly differ and are 1.39 p/v-km (Nijland and van Meerkerk, 2017) and 4.59 p/v-km (Mitropoulos and Prevedouros, 2014). Fagnant and Kockelman (2014) do not state the assumed load factor of autonomous ride hailing vehicles but state that these could replace up to 11 private vehicles. Moreover, the authors computed an additional 10% of vehicle travel due to the provided pick-up service.

Four papers apply a consequential LCA approach. Baptista et al. (2014) and Martin and Shaheen (2011) subtract saved carbon emissions by using a private vehicle from carbon emissions caused by car sharing vehicles. Chen and Kockelman (2016) subtract avoided carbon emissions from diminished parking space needed for car sharing in contrast to private vehicles.
Chen and Kockelman (2016) and Briceno et al. (2005) assess effects of car sharing on other transport modes (rail, bus and aircraft). Briceno et al. (2005) evaluate indirect economy-wide effects caused by car sharing programs which is referred to as an indirect rebound or backfire effect (Saunders, 2000). Kjaer et al. (2016) describe rebound effects in general as crucial for evaluating PSS' environmental performance.

Mentioned challenges by authors are mainly directed at data quality issues. Nijland and van Meerkerk (2017) highlight the challenging nature of establishing reliable causal relationships between joining car sharing and subsequent altered mobility behaviour. According to the authors, several parameters like changes in users personal lives can influence individual mobility behaviour and selected modes of transport. Chen and Kockelman (2016) find it challenging to include economy-wide rebound effects due to data insecurity. Likewise, Briceno et al. (2005) stress that included rebound effects are assumptions only. Kjaer et al. (2016) accentuate the challenge of assessing the environmental impacts of PSS before they are introduced to the market. PSS like mobility services can lead to profound changes in user experiences in a society which characteristics are yet to be discovered. Therefore, the validity of such ex-ante studies is limited. Due to the difficult data basis in mobility service research, 64% of the publications apply a scenario approach in order to show a range of modelling results and respective conclusions. Kjaer et al. (2016) recommend to always perform scenario analyses when evaluating the environmental impacts of PSS. Fagnant and Kockelman (2014) are the only authors including empty travels as they assess ride hailing life cycle CO_2 emissions.

2.4.3 Summary

In this sub-chapter, the literature review's research question is addressed by summarising common characteristics of LCA-based approaches to compare life-cycle carbon performances of private and mobility service vehicles.

The majority of studies assesses the vehicles' whole life cycle. Comparisons of carbon performances of service and private vehicles are facilitated by using 'p-km' as reference unit. As such, varying load factors can be considered across different transport modes. Poor data quality or lack of data is met with scenario-building. Mostly ICE-powered car sharing vehicles are compared to private vehicles. Ride pooling vehicles with higher load factors than car sharing and ride hailing were not evaluated in the selected studies. Ride hailing's pick-up service induces empty travels which is included in the LCA study. Including rebound effects in the analysis is considered as crucial. However, the authors recognize that calculations of rebound effects in LCA studies of mobility services is, even on city level, based on assumptions only. Examples for such rebound effects based on unreliable data include saved parking space, replacement rates of service versus private vehicles and economy-wide backfire effects. The private sector is least addressed in the selected case studies. The research gap of applying the LCA methodology on fleets comprised of private and service vehicles from an OEM's point of view is thus accentuated.

2.5 Deficit analysis

In this section, the state of current academic knowledge regarding the research objective of this dissertation is analysed for its ability to answer the main research question. By addressing shortcomings, the research gap is further delineated.

The research field of corporate carbon management is dominated by conceptual frameworks and theoretical studies which do not provide detailed guidance on how to model future emissions nor on how to evaluate reduction measures on organisational level over time. As Burritt et al. (2011) put it, the reason might be that no single best carbon management approach exists so that every company, resp. every sector, needs to elaborate its own approach. As such, companies are able to develop their carbon management approach according to general recommendations found in the corporate carbon management literature. Regarding the research objective of this dissertation, these recommendation are (1) setting-up a resource-efficient carbon management which draws on existing carbon-information systems, (2) based future emissions projections on past emissions data in order to cover the same scope of emissions and (3) evaluating emissions along the life cycle of products and services offered.

Current carbon accounting approaches of OEMs are not suitable to model future emissions in relation to a given carbon budget. They aim at answering the question: "What are the organization's past year absolute carbon emissions?". Existing approaches are stationary and past-oriented calculating an OEM's absolute emissions within a defined timespan. The information needed to compute emissions like fleet averages, sales volumes and energy consumption of manufacturing sites is available. Vehicle LCA studies, emission factors derived from LCA databanks and TTW fleet emission averages have been shown to be the dominant information source to calculate company-level emissions. The to-be-developed CBC method aims at answering the question: "How can the OEM stay within a given carbon budget until 2050?". Therefore, the holistic examination of future scope 1-3 emissions in relation to a carbon budget is necessary. Meeting this goal is not possible by using current approaches as these cannot calculate emissions over several years in relation to a carbon budget. Moreover, scope 1 and 2 emissions and each scope 3 category are calculated separately, i.e. the interconnectivity of different parameters influencing emissions arising over the life cycle of vehicles on fleet level cannot be depicted. For example, stricter fleet emission averages lead to increasing shares of BEVs (cat. 11). In turn, material supply chain emissions (cat. 1) will increase accordingly. These linkages must be captured in a dynamic model.

OEMs will strive for achieving CO_2-reduction targets with the least additional effort to business-as-usual activities. A follow-up question is therefore: "Can the organization stay within the carbon budget when complying with fleet emission legislations and while increasing sales volumes according to the average sector growth?" To answer this question, the CBC method must be able to compute powertrain fleet mixes suitable to comply with market- and time-specific fleet emissions legislations and include projections on future vehicle sales. In case the carbon budget cannot be met within this least-effort approach, promising carbon reduction measures at the vehicle level must be extrapolated to and quantified on fleet level. A respective question is: "Can the OEM stay within the carbon budget when providing BEVs over their lifetime kilometrage with renewable energy?" Here, again the need for a holistic approach is highlighted: the effect of the reduction measure is related to the amount and size of BEV vehicles in each market.

Past-oriented approaches account for carbon emissions of the entire OEM Group, i.e. of all associated brands. Likewise, to comply with a carbon budget, the entire OEM Group must reach carbon reduction targets. However, brands have different foci and will each develop in a specific way. Future absolute CO_2 emissions must therefore be modelled brand-specifically. As such, the question towards the CBC method can be refined further. For example: "Can the OEM stay within the carbon budget when providing BEVs of brand X over their lifetime kilometrage with renewable energy?".

In order to answer these types of questions, the CBC method must deal with high data insecurity concerning the future development of the parameters influencing OEMs absolute emissions. Although past-oriented approaches do not have scenario-building power, data gaps are already dealt with in the calculation of material supply chains. Models without a specific LCA study are allocated to the study of a comparable model. Future models' material supply chain emissions could also be modelled based on available LCA studies until specific studies are finalised.

The predicted increasing demand for mobility services instead of private vehicles and its impact on OEMs' future carbon emissions cannot be analysed within current approaches. Neither the effect on vehicle production volumes nor implications for fleet composition in terms of vehicle sizes and powertrains on OEMs' emissions can be computed so far. Hence, the question "Can the OEM stay within the carbon budget when providing mobility services instead of private vehicles according to the predicted demand?" remains so far unanswered. However, LCA-based comparisons of private and mobility services vehicles' carbon performances exist as shown in the literature review. Merging these with existing past-oriented LCA-based company-level emissions calculations and forecasts on mobility demand is necessary to address the research objective. In order to include different mobility services in OEMs' fleets from an LCA point of view, the reference unit needs to be modified from v-km to p-km. Only when information on the amount of p-km offered by each private or service vehicle is included by considering varying load factors can the effect service vehicles have on fleet size be included. Furthermore, empty travels of ride hailing and pooling vehicles must be included as these lower the total provision of p-km per service vehicle.

An OEMs' 2 °C-compatible carbon reduction target resp. carbon budget can be externally calculated and verified by SBTi. CDP is part of the initiative and progress towards achieving a verified target is monitored based on past reported emissions. This approach fits the recommendation to base future emissions modelling on the scope of past reported emissions. If OEMs' future computed emissions in the CBC method match the scope of past emissions they also match the carbon budget's scope. However, the challenge remains to merge emissions computing with a given carbon budget in order to derive recommendation for reduction measures and fleet composition from the modelling results.

3 Method development

Based on the deficit analysis above, requirements for the CBC method are formulated. Sub-research question 3 ("Which requirements does the method need to meet in order to represent a high degree of scientific quality as well as practical applicability?") is addressed. Following the approach by Weihofen (2016), requirements are two-fold as both methodological accuracy of modelling results and practical applicability by OEM carbon practitioners must be ensured.

3.1 Methodological requirements

Computing future carbon emissions based on past emissions is the basic prerequisite for the CBC method. The requirement *future-orientation* refers to the method's ability to integrate a higher degree of external information in emissions calculation. Such external information includes mentioned projections on vehicles sales, fleet emissions averages and electricity mixes. The ability to deal with changing input parameters includes the method's ability to compute scenarios. Scenario-building power has been shown to be vital when dealing with high data insecurity as is the case with projection until 2050.

As absolute CO_2-reduction targets calculated with SBTi methodology are based on and monitored by reported scope 1-3 emissions to CDP, the CBC method must cover the same scope of emissions. The requirement *scope 1-3* hence describes the need to model the same scope of emissions reported in the past. Several scope 3 categories are classified as "irrelevant" for their GHG inventory by OEMs. "Scope 1-3" therefore does not require to include irrelevant categories in future emissions modelling.

Modelling time series of an OEM's emissions is key to depict compliance with the carbon budget allocated to the company. The requirement *carbon budget* describes the method's ability to relate each modelling point (e.g. years 2010-2050) to the available carbon budget. The requirement includes allocating CO_2 emissions to years that were not modelled with specific data. For example, if data is only available in five-year-steps, the missing four years must be interpolated to diminish the carbon budget accordingly.

In case computed emission pathways until 2050 exceed the carbon budget, reduction measures tackling carbon hotspots must be quantified at the company level. The requirement *reduction measures* describes the necessity to compute the impact of reduction measures over the life cycle of vehicles on fleet level. Measures showing high carbon reduction potential at the vehicle level must be extrapolated according to time-, market- and brand-specific fleet compositions. *Reduction measures* thus refers to modifying data inputs at the vehicle level like CO_2 emitted during manufacturing of LIBs and relating it to the number and battery capacities of BEVs in the fleet. This requirement includes manipulating emissions data derived from vehicle LCAs currently used to calculate material supply chain emissions (scope 3 cat. 1). As shown in Figure 21, vehicle LCAs need to be modularised to compute supply chain reduction measures on fleet level. As such, there is no need to generate new vehicle LCAs for every reduction measure as only one input parameter must be changed.

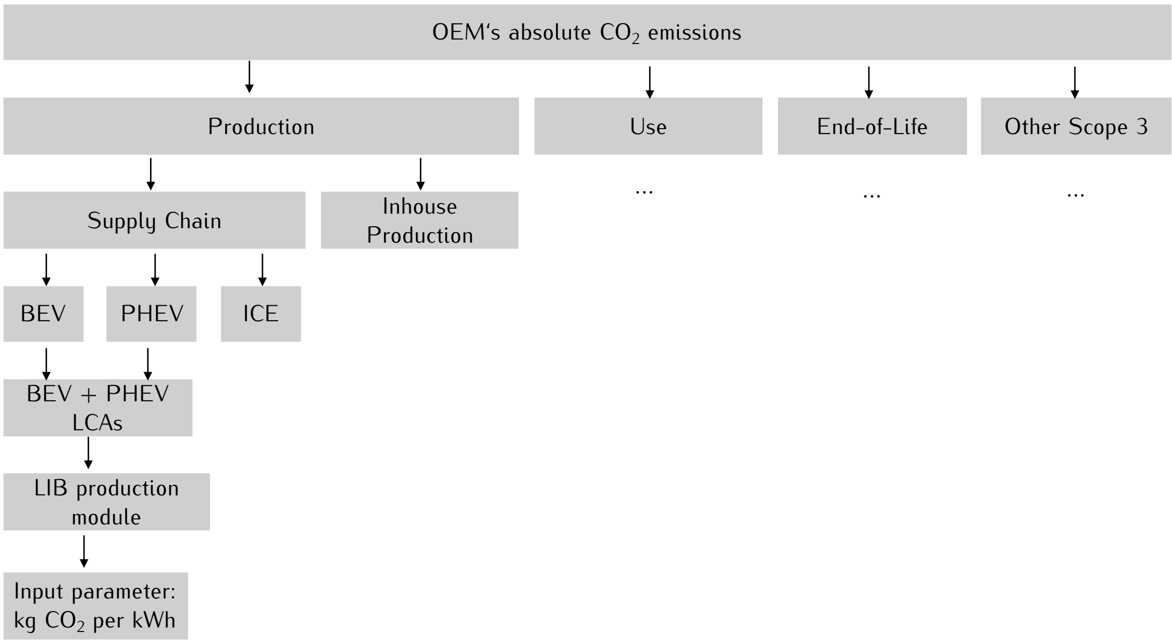


Figure 21 Exemplified modular approach to quantify reduction measures at the company level.

Next to electrified powertrains, mobility services have been shown to be a major parameter influencing OEMs' future business. Therefore, modelling the impact of partly selling mobility services instead of private vehicles on OEMs' future emissions is necessary to give indications whether or how the carbon budget will be met. The requirement *mobility services* describes the method's ability to include market- and time-specific projections of mobility demand for mobility services and compute the respective impact on fleet size and powertrain composition. According to the analysis above, types of mobility services to be included are car sharing, ride hailing and pooling. A summary of methodological requirements to be met by the CBC method is provided in Table 10.

Table 10 Methodological requirements to be met by the CBC method.

Methodological requirement	**Description (short)**
Future-orientation	Including projections concerning vehicle sales, fleet emission averages etc. in scenarios depicting future absolute emission pathways.
Scope 1-3	Covering same emission scope used in past emissions reporting.
Carbon budget	Relating annually modelled emissions to a given carbon budget. Interpolating non-modelled years linearly to produce complete emission time series.
Reduction measures	Extrapolating hotspot carbon reduction measures at the vehicle level to fleet levels. Using a modular approach to prevent need for new LCA studies at the vehicle level.
Mobility services	Including projections of mobility demand for mobility services (car sharing, ride hailing, ride pooling) in modelling process to quantify impact on fleet size and composition.

3.2 Practical requirements

Compatibility with existing carbon accounting approaches is necessary to cover the same scope of emissions and for the CBC method to work resource-efficiently. The requirement *compatibility* refers to using, as far as possible, the same data sources and flows in the CBC method as in current carbon accounting. This includes e.g. the use of representative vehicle LCAs to calculate material supply chain and EoL emissions and the use of environmental information systems to compute scope 1 and 2 emissions (in-house production). Furthermore, both corporate carbon practitioners and managers must comprehend the functioning of the CBC method to assess the significance of modelling results. The requirement *comprehensibility* describes the need for transparency of data sources and assumptions used to generate results. A high degree of transparency enhances credibility and reliability of methods dealing with environmental information (Schwegler et al., 2011). Brands within one OEM Group focus on different markets and fleet mixes. The practical requirement *company structure* therefore describes the method's ability to model emission pathways specifically for each brand and to eventually sum up brands' emissions to Group emissions.

Table 11 Practical requirements to be met by the CBC method.

Practical requirement	Description (short)
Compatibility	Ensuring compatibility with data sources and flows of current carbon accounting approaches.
Comprehensibility	Ensuring transparency of functioning and assumptions made to produce modelling results.
Company structure	Modelling emission pathways of OEMs' brands separately.

3.3 Definition of requirements

Future-orientation

Requirement *future-orientation* aims at the method's ability to compute future emission scenarios based on reported past emissions of sold vehicles. The main drivers (except mobility services, see below) influencing future absolute emission of OEMs identified in 2.2.3 are:

- Demand for LDVs
- Fleet emission averages
- CO_2 intensity of electricity mixes

The evaluation question for this requirement is formulated as follows: "Can input parameters concerning main emission drivers be changed to model future emission scenarios?". Table 12 depicts the evaluation parameters with respective definitions.

Table 12 Evaluation parameters for requirement "Future-orientation".

Symbol	Meaning	Definition
●	Yes	Main emission driver input parameters can be adapted within the method to match future projections of their developments.
◑	Partly	At least one of the main emission driver input parameters can be modified.
○	No	No input parameters can be modified.

Scope 1-3

Requirement *scope 1-3* targets the method's ability to cover scope 1-3 emissions according to GHG Protocol. Some scope 3 categories are considered "irrelevant" by OEMs and are not reported. Such irrelevant categories are thus excluded from this requirement. The evaluation question for this requirement is: "Are scope 1-3 emissions covered?". Table 13 depicts the evaluation parameters with respective definitions.

Table 13 Evaluation parameters for requirement "Scope 1-3".

Symbol	Meaning	Definition
●	Yes	Scope 1-3 emissions according to GHG Protocol are covered.
◑	Partly	At least life cycle CO_2 emissions of sold products are covered on company-level (manufacturing, use and EoL phases).
○	No	No CO_2 emissions on company-level are covered.

Carbon budget

The requirement *carbon budget* targets the method's ability to relate a company's annual absolute CO_2 emissions to a predefined carbon budget to be used until 2050. This requirement entails computing emission time series, i.e. summarising modelled annual emissions from a base year until target year 2050. *Carbon budget* also includes the method's ability to interpolate linear emission pathways between two modelling points. This is necessary as projections for the development of main emission drivers might not be available for each year. The evaluation question for this requirement is: "Are annual company-level CO_2 emissions related to a predefined carbon budget?". Evaluation parameters can be found in Table 14.

Table 14 Evaluation parameters for requirement "Carbon budget".

Symbol	Meaning	Definition
●	Yes	Depending on input parameters for specific years and interpolation of non-specifically modelled years absolute emissions from base to target year are summarised and put in relation a predefined carbon budget.
◑	Partly	Modelling time series of annual company-level CO_2 emissions is possible. Annual emissions can be summarised to indicate the company's carbon emissions over several years.
○	No	Emission time series are not computed.

Reduction measures

Requirement *reduction measures* targets the method's ability to extrapolate hotspot carbon reduction measures from vehicle to fleet levels. It entails the possibility to manipulate input parameters at the vehicle level according to a known carbon reduction potential of a specific measure. The prerequisite is a modular approach to modelling emissions. The calculation of single categories like e.g. scope 3 category 1 (supply chain emissions) must be divisible into sub-modules calculating emissions for specific product classes. The sub-module must be designed in a way that it can be disaggregated further into modules computing emissions of the process to be tackled by the respective measure (e.g. LIB production within material supply chain emission calculation of BEVs).

This requirement also includes the method ability to calculate a company's absolute emissions dynamically, i.e. parameters at the vehicle level need to be related to corresponding parameters on fleet level. For example, reduction measures targeting BEVs should only be extrapolated to the time-, market- and brand-specific amount of BEVs in the OEM's fleet omitting other powertrains. The evaluation question for this requirement is: "Can CO_2-reduction measures be extrapolated from vehicle to fleet level?". Defined evaluation parameters are found in the following table.

Table 15 Evaluation parameters for requirement "Reduction measures".

Symbol	Meaning	Definition
●	Yes	Single modules within the modelling of company-level CO_2 emissions are available for modification below vehicle level. Modelling of emissions is product-class-specific so that extrapolation to fleet level is possible based on fleet level input data.
◑	Partly	Reduction measures can be quantified at the vehicle level and related to company-level input data. Though single modules below vehicle level cannot be modified on their own.
○	No	Quantification of reduction measures on company-level is not possible.

Mobility services

Requirement *mobility services* refers to the method's ability to include projections on demand for car sharing, ride hailing and ride pooling by quantifying the impact on fleet sizes and powertrain composition. As projections for mobility service demands are mainly published in market-specific shares on overall mobility demand, the method must be able to convert information regarding to-be-provided p-km in OEM-specific vehicle sales numbers. The evaluation question for this requirement is: "Can the impact of demand for mobility services on OEM's fleet size and powertrain composition be quantified?". Defined evaluation parameters are found in the following table.

Table 16 Evaluation parameters for requirement "Mobility services".

Symbol	Meaning	Definition
●	Yes	Projected shares of market-specific demand for different mobility services are used as input parameters to calculate OEM's fleet sizes and composition and consequently company-level CO_2 emissions.
◑	Partly	Projected shares of at least one type of mobility services is used to calculate OEM's fleet sizes and composition and consequently company-level CO_2 emissions.
○	No	Information on future mobility service demand cannot be integrated.

Compatibility

Requirement *compatibility* targets the method's ability to adopt, whenever possible, same data sources as in current carbon accounting approaches. This entails computing emissions arising from material supply chains and EoL of sold vehicles to be calculated via vehicle LCAs, basing scope 1 and 2 emissions modelling on carbon data originating from environmental information systems and using market-specific fleet emission averages as basis for TTW and WTT emissions computing. As such, additional effort for additional data generation is kept to a minimum. The evaluation question for this requirement is: "Are data sources and flows compatible with current carbon accounting approaches?". Defined evaluation parameters are found in Table 17.

Table 17 Evaluation parameters for requirement "Compatibility".

Symbol	Meaning	Definition
●	Yes	Modelling future company-level scope 1-3 emissions is based on the same data flows as in past-oriented accounting approaches.
◑	Partly	Product LCAs are the main data source to calculate company-level scope 1-3 emissions.
○	No	Product LCAs are not used as main data sources.

Comprehensibility
Requirement *comprehensibility* aims at ensuring that relevant aspects of the method's processes are being understood by various stakeholders as comprehensibility of models raises the possibility of their adoption (Gleicher, 2016). Both Weitlaner et al. (2013) and Gleicher (2016) recommend using graphic data visualisation to increase comprehensibility of modelling methods. The range of the CBC method's stakeholders is broad: corporate carbon practitioners, managers as well as anybody affected by decisions made based on its modelling results. Adopting a clear and precise language for method description is therefore suggested (Weitlaner et al., 2013). Gleicher (2016) i.a. distinguishes in ensuring the comprehensibility of data inputs, assumptions and equations used in modelling. Based on Weihofen (2016) *comprehensibility* therefore entails the following sub-requirements:

- Clear structure of data sources and flows
- Low degree of complexity in equations
- Precise and plain language used for explanations

The evaluation question for this requirement is: "Are the method's functioning and data flows comprehensible?". Defined evaluation parameters are found in the following table.

Table 18 Evaluation parameters for requirement "Comprehensibility".

Symbol	Meaning	Definition
●	Yes	All three sub-requirements are met.
◑	Partly	At least one or two sub-requirements are met.
○	No	None of the sub-requirements in met.

Evaluation parameters for requirement *comprehensibility* are of a more subjective nature than those of the other requirements. It should be noted that the author's perception of e.g. "low degree of complexity in equations" determines the evaluation results.

Company structure
Requirement *company structure* refers to the method's ability to compute absolute emissions of brands resp. company entities separately to eventually summarise emissions on company-level. The underlying model to compute brands' emissions is the same for every entity. Though the possibility to use specific data inputs for each brand must be given. The evaluation question for this requirement is: "Can brands' absolute emissions be calculated separately?". The evaluation parameters are defined in Table 19.

Table 19 Evaluation parameters for requirement "Company structure".

Symbol	Meaning	Definition
●	Yes	Corporate entities' emissions are calculated in the same manner but separately to be summed up eventually at the company level.
◑	Partly	Corporate entities' emissions are calculated based on different models and are summed up eventually at the company level.
○	No	Emissions are calculated at the company level only.

3.4 Screening of methods

In the following, available methods are presented and screened for compliance with the above requirements. The methods are selected based on their topical overlap with the to-be-developed CBC method. First, methods used to calculate CO_2 emissions on company-level, second, promising methods assumed to cover several of the requirements are screened. Selected methods are first described and, in the following, evaluated based on the developed methodological and practical requirements. Description of methods makes no claim of completeness but focuses on aspects relating to requirements of the CBC method. If applicable, an exemplary implementation of the screened methods by OEMs is described.

3.4.1 Organisational Life Cycle Assessment (O-LCA)

The Organisational Life Cycle Assessment (O-LCA) is an environmental multi-impact approach to assess the environmental performance of companies and other organisations. This subchapter is based on Martínez Blanco et al. (2015) unless otherwise indicated. Like product LCA studies, O-LCA promotes a cradle-to-grave approach to avoid environmental burden shifting between life-cycle phases and is aligned with ISO 14040 and 14044 (ISO, 2006a, 2006b). On organisational level, the advanced ISO/TS 14072 refers to O-LCA as "a compilation and evaluation of the inputs, outputs and potential environmental impacts of the activities associated with the organisation adopting a life-cycle perspective" (ISO, 2014; Martínez Blanco et al., 2015, p. 30). The method aims at serving analytical ends which in turn supports strategic decision-making by managers. For example, analysing environmental hotspots can support the development and prioritisation of (sub-)targets. Knowledge on the composition of the organisation's environmental impact and quantification of improvement options can help managers to pass measures fitting the accomplishment of an internal or external target. O-LCA is also meant to be used as information source to report environmental performances to third parties such as CDP. Next to the standard life-cycle phases covered in a product LCA ("manufacturing", "use", "EoL"), O-LCA's developers recommend including environmental inputs and outputs arising from other direct and indirect activities normally excluded in product LCAs. These activities include employee commuting, business travel, franchising and capital equipment which are mainly based on recommendations by GHG Protocol (WBCSD and WRI, 2004) and Organisation Environmental Footprint Guide (OEF) (EC-JRC, 2012). Similarly, calculating emissions regarding these additional activities is proposed to be based on GHG Protocol and OEF. Handling of multi-source data flows is described within the O-LCA workflow.

Equally to product LCAs, O-LCA's workflow consist of the iterative phases (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation.

(1) Goal and scope definition
In O-LCA's first phase, goal and scope of the study should be clearly defined. The elements to be defined are i.a.:

- Organisation to be studied
- Products, operations, facilities and sites of the organization included in the reporting organisation
- Reference period
- Reporting flow
- System boundary
- Data (quality) requirements
- Assumptions
- Limitations

The reporting organisation, e.g. a corporation, can be defined by distinguishing between included brands with respective products and operational regions. For example, in case of an OEM with several brands, the reporting organisation could be defined as: OEM's brands A-D active in markets X-Z. The calculation's reference period is proposed to be one year in accordance with reporting schemes like CDP. The reporting flow is similar to a product LCA's functional unit. It indicates the type and amount of outputs of the reporting organisation within the reference period. In case of an OEM, the reporting flow could be numbers of LDVs sold in the past reporting year. The system boundary determines which processes are part of the organisational system under study. For example, it is determined how many upstream and downstream supplier-tiers are considered. ISO/TS 14072 specifies that organisations' products generating emissions during use phase (like e.g. OEMs' vehicles) must include these downstream emission in their system boundary. As in product LCAs, the use of generic process data from LCA databases is allowed. A figure visualising the study's system boundaries is recommended. An exemplified visualisation of an OEM's O-LCA system boundaries is depicted in Figure 22.

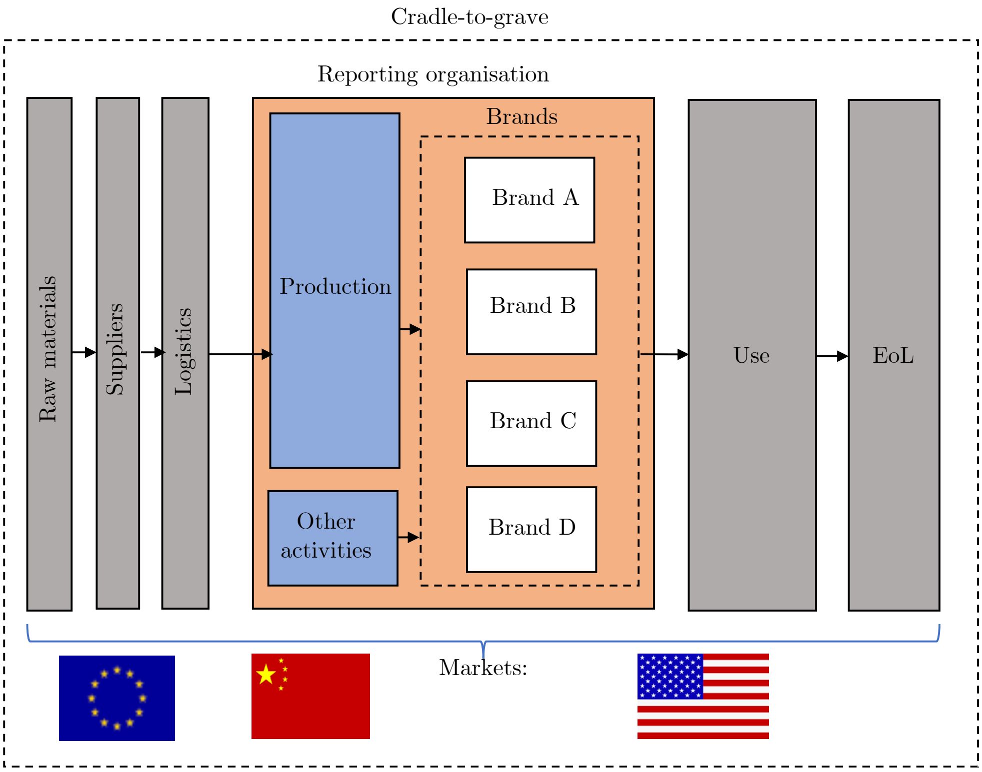


Figure 22 Exemplified visualization of a reporting organisation's O-LCA system boundaries based on UNEP (2015).

(2) Life cycle inventory analysis

O-LCA's life cycle inventory analysis includes all inputs and outputs necessary to produce the reporting flow. The inventory is comprised of elementary flows only. Data sources and quality used should be clearly stated to reveal possible limiting factors of the study's results. Within the bottom-up data collection approach, different product LCAs are weighted and summarised according to the composition of the organisation's portfolio. In case no specific LCAs for each product offered exist, product clusters can be defined. Clusters represent a group of products which inputs and outputs are based on a single "cluster-LCA study", i.e. the LCA of a representative product. Eventually, cluster-LCA studies are weighted and summarised according to the composition and size of the product portfolio in the reference period. Inputs and outputs related to other activities like employee commuting etc. should be added on top in case this is required by the goal and scope definition. Data collection can also be performed top-down or within a hybrid bottom-up/top-down approach. In accordance with GHG Protocol Scope 3 Standard, data collection efforts should be focused on areas causing highest environmental impacts and/or promise impact reduction opportunities.

(3) Life cycle impact assessment

O-LCA's impact assessment phase is "[…] basically the same as that of product LCA […]" (Martínez Blanco et al., 2015, p. 77). Environmental flows are converted into environmental impacts based on the available impact assessment methods. Both midpoint and endpoint-level impact assessment is possible. See chapter 2.1 for an introduction to the (product-oriented) LCA methodology.

(4) Interpretation

O-LCA's interpretation phase aims at evaluating the results of the life cycle inventory analysis (and life cycle impact assessment). Here, conclusions are drawn and put in perspective of aforementioned limitations and regarding the system boundaries. According to the respective goal and scope definition hotspots on different levels such as brands, markets, products can be evaluated. Based on the interpretation of results, recommendations for future steps like e.g. reduction measures can be developed.

Once an organisation's O-LCA model is finalised it can be used as a basis to build scenarios quantifying the impact of proposed reduction measures. For example, a certain energy source has been identified as a hotspot for a certain environmental impact. By simulating a change in energy source in the respective product LCAs and subsequently extrapolating the effect to organisational level, the impact of operationalising this measure is computed. In case existing product LCAs do not offer sufficient data quality or disaggregation, new LCA studies might have to be produced to quantify a certain environmental impact improvement measure. As for goal and scope definition, scenario-building requires a clear description of the model's assumptions and limitations.

Additionally, O-LCA can be used as environmental performance tracking tool either for "passive" monitoring or "active" monitoring of the organisation's performance regarding an internal or external target. According to ISO/TS 14072, reference period, system boundaries as well as the reporting organisation itself need to be coherent over the reporting years to ensure consistency of modelling results. Changes in company structure over time, e.g. new brands, are, however, tolerated.

Evaluation of Organisational Life Cycle Assessment (O-LCA)

O-LCA is a comprehensive method to assess companies' environmental emissions and impact from a life-cycle perspective. Albeit being a multi-impact approach, the method allows to only focus on carbon emissions when focusing on the life cycle inventory phase. It is well-renown method which has been applied by different sectors including the textile and cosmetics industry with diverse product portfolios (see e.g. de Camargo et al., 2019; Resta et al., 2016).

The requirement *future-orientation* aims for methods to be able to build scenarios by changing the data inputs for OEM's main future emissions drivers. Once a basic O-LCA model is finished, scenarios can be modelled by changing input parameters of the basic or reference year model. The authors state that an evolving reporting flow, i.e. an evolving production or sales output, requires for the model to be recalculated (Martínez Blanco et al., 2015). Hence, building future emission scenarios within O-LCA basically refers to setting up a new model respectively using existing cluster-product LCAs and weighing them according to future product portfolios. With O-LCA it would be possible to set up a reference year model of an OEM's absolute carbon emissions by using product-LCAs of different vehicle sizes and powertrains representing specific vehicle classes or clusters. These vehicle-cluster-LCAs would be weighted and aggregated according to the number of overall vehicles sold, shares of powertrain, vehicle sizes etc. Until now, no O-LCA model of an OEM is publicly available to analyse such a model specifically. A future-emissions-scenario could be built by modifying the number of vehicles sold and shares of powertrains etc. according to internal or external projections. Future market-specific CO_2-intensities of electricity mixes cannot be modified as one set of input parameters but need to be changed within the cluster-LCAs used. This means that for every market- and time-specific electricity mix new cluster-LCA studies would have to be generated. Furthermore, it is not possible to calculate what fleet composition scenario is suitable to meet respective time- and market-specific fleet emission averages within the O-LCA model. This calculation as well as computing future fleet sizes based on growth projections must be performed outside the O-LCA model. The new input data would be transferred back into the scenario-model manually.

In summary, O-LCA offers the possibility to compute future scenarios based on past emissions data which allows for modifying input parameters for OEM's main emissions drivers (a) demand for LDVs and (b) CO_2 intensity of electricity mixes. Calculating product portfolios suitable to meet specific fleet emission averages is, however, not possible. O-LCA therefore only partly meets the *future-orientation* requirement. Table 20 provides an overview of O-LCA's evaluation of all requirements.

Requirement *scope 1-3* is fully met by O-LCA. Not only are emissions arising from products' life cycles covered but additional direct and indirect activities and their resulting emissions are included. The O-LCA guidance document specifically references GHG Protocol and recommends using their handbook for calculating emissions of supporting activities like employee commuting. By applying O-LCA it is therefore possible to cover the same scope of emissions as OEMs' past reported carbon emissions to CDP.

Requirement *carbon budget* refers to modelling emission time-series related to a fixed carbon budget. When applying O-LCA, a company's base year carbon emissions can be calculated as well as annual past emissions can be monitored. Likewise, future annual emissions can be computed. In case O-LCA would be used to model absolute emissions pathways of OEMs from e.g. 2010 to 2050, the models for each past year's emissions as well as the models for every coming year until 2050 would have to be built. Subsequently, absolute modelled emissions of forty years would be summarised to demonstrate the total amount of carbon emissions produced during that timespan. The O-LCA therefore partly meets requirement *carbon budget*. In order for the method to fully meet the requirement, each year's emissions would be automatically related to a carbon budget by e.g. visually indicating the amount of budget used so far. Also, in the O-LCA every year has to be modelled specifically; a (linear) interpolation between two modelling point is not possible.

O-LCA can be used to quantify reduction measures on product level and extrapolate the effect to company level according to the composition and size of the product portfolio. Via generating new cluster-LCAs, the effect of e.g. an alternative electricity source within the manufacturing phase of a product can be computed. It is, however, not possible to extract sub-modules from the respective cluster-LCAs to modify specific input parameters without generating a complete new product LCA study. To quantify the effect of e.g. an alternative electricity mix in LIB production, all cluster-LCAs containing LIB production (i.e. several BEV and PHEV LCA studies) would have to be generated anew. O-LCA therefore only partly meets the *reduction measures* requirement.

Mobility services requirement introduces the requirement to model company-level emissions of an OEM partly changing its business model and therefore product and service portfolio. This requirement is OEM-specific as it specifically refers to the conversion of mobility service demand in needed numbers of vehicles. As O-LCA is a method suited for all kinds of industries it does not include specific features for automotive OEMs. Though the method is based on product LCA standards ISO 14040 and 14044 which include the assessment of goods and services alike (ISO, 2006b, 2006a). The O-LCA developers refer to quantifying environmental impacts associated with organisations offering services as "challenging" especially when relating them to sold products (UNEP, 2015, p. 49). The authors therefore recommend using reporting flows other than products like economic figures. In case of OEMs seeking to compute their absolute emissions until 2050, the reporting flow's unit must stay the same before and after introducing mobility services into their portfolio. Hence, CO_2 emissions arising over the life cycle of sold vehicles and mobility services must both be related to the number of vehicles produced and sold resp. driven to offer mobility to customers. As life-cycle carbon emissions of private vehicles and mobility services are compared and related to each other on the basis of p-km, the calculation translating demand for certain mobility services in needed amount and type of vehicles would have to be performed outside the O-LCA model. Accordingly, modified figures concerning size and powertrain composition of fleets could subsequently be used as input for an O-LCA scenario-model. This calculation would also have to be aligned with fleet emissions averages, i.e. fleet sizes and compositions including both vehicles sold and mobility services offered also have to comply with market- and time-specific fleet emissions averages. As information on future demand for mobility services cannot be integrated in O-LCA models, requirement *mobility services* is not met.

Throughout the O-LCA guidance document, the GHG Protocol is referenced and recommended to be consulted for calculation approaches. O-LCA's compliance with requirement *scope 1-3* indicates a basic compatibility with emissions reported to CDP as the same scope is covered. Similar to OEM's past-oriented carbon accounting approaches different scopes/categories are calculated within different modules in O-LCA although the terminology used differs slightly. Direct activities ("scope 1-2 emissions" in GHG Protocol terms) should stem from high data quality sources such as measured data from EMS. This proposed approach is in line with current data flows in OEM's scope 1-2 emissions reporting. Indirect upstream and downstream activities ("scope 3 emissions" in the GHG Protocol) are allowed to originate from more generic data sources such as product LCAs. This is in line with OEMs' stated approaches to calculate both material supply chain and EoL carbon emissions which are based on LCA studies weighted according to size and composition of the product portfolio. Furthermore, upstream and downstream supporting activities (i.e. scope 3 categories mostly classified as "irrelevant" by OEMs) are mostly calculated based on averaged or generic data according to OEMs' calculation approaches published on the CDP platform (CDP, 2018a). OEMs' main emissions source, the sold vehicles' use phase, is calculated in a more specific way for CDP reporting than proposed in O-LCA guidance. OEMs calculate use phase emissions of sold vehicles based on market-specific fleet emissions averages which are used to calculate both TTW and WTT emissions. This quite specific approach pursued by OEMs might be due to market-specific legislations controlling CO_2 emissions of their products' use phase which is different to other industries' use phase emission calculation which is not dependent on legislative thresholds. Requirement *compatibility* is only partly met by the O-LCA methodology as not all data sources and flows used by OEMs to calculate past carbon emissions are the same. Although O-LCA emissions calculation relies mostly on data derived from product LCAs, regionalised use phase emissions calculation is not a designated approach though being significant for carbon emissions reporting by OEMs.

Requirement *comprehensibility* aims at testing methods for the comprehensibility of their general functioning and data flows. The O-LCA methodology is described in a very structured and understandable way in its guidance document. Requirements for data quality are defined and exemplary data flows are visualised throughout the document. O-LCA practitioners are asked to produce diagrams graphically describing data sources and flows used. Precise and functional language is used by the authors to guide practitioners through the guidance document. As O-LCA mostly adopts the workflow for producing product LCAs, work steps are clearly laid out asking practitioners to analyse their models for assumptions and limitations that might lessen the informational value of results respectively should be considered when decisions are based on the modelling results. For O-LCA a specific ISO standard was developed ensuring the transparency of the method's every aspect (ISO, 2014). Although the guidance document is extensive, O-LCA relies on straightforward calculations which are clearly described. In summary, O-LCA meets all sub-requirements of the *comprehensibility* requirement.
O-LCA is suited for corporation with both diverse or homogeneous product portfolios. It is explicitly directed to companies with several product lines or brands. Brands' emissions can be calculated in the same manner in case the same products are offered or based on different sub-models. OEMs applying O-LCA can use the same cluster-LCAs to base extrapolation of emissions to fleet level upon for different brands though weighing them according to the brands' different fleet sizes and compositions. Requirement *company structure* is therefore fully met by O-LCA method.

Table 20 Summary of evaluation of requirements for O-LCA.

Meta requirement	Requirement	Evaluation
Methodological quality	Future-orientation	◑
	Scope 1-3	●
	Carbon budget	◑
	Reduction measures	◑
	Mobility services	○
Practical applicability	Compatibility	◑
	Comprehensibility	●
	Company structure	●

3.4.2 Organisation Environmental Footprint (OEF)

The Organisation Environmental Footprint (OEF) was developed by the European Commission (EC) in 2012 to provide a method for multi-criteria assessment of organisations' environmental performance adopting a life-cycle perspective. This sub-chapter is based on European Commission (2012) unless otherwise indicated. Although the O-LCA approach described above is extensively based on the OEF Guidance, the implementation of both methods partly differs (Neppach et al., 2017). Therefore, the OEF method is separately analysed. OEF was developed in unison with the Product Environmental Footprint (PEF). PEF provides the basis for standard environmental assessments of products within certain product categories aiming at comparing different performances (Bach et al., 2018). According to European Commission (2012), an OEF should give the same result as a summary of PEFs for all products produced by the reporting organization provided over the same reporting period. OEF was developed based on other existing organisational environmental footprinting methods used for reporting purposes such as the Bilan Carbone method (Pelletier et al., 2014). The guidance document aims at establishing rules for consistent modelling of OEF studies. A finished OEF study can foster the understanding of a company's environmental hotspots, possible counteracting measures as well as serve as a basis for strategic decision-making. To make OEFs of companies within one sector comparable, specific sector-rules called OEFSRs were developed. Similar to product LCA studies based on ISO 14040 (2006b) and ISO 14044 (2006a) work packages for generating an OEF are (1) goal definition, (2) scope definition, (3) resource use and emissions profile, (4) environmental footprint impact assessment, (5) interpretation and reporting and (6) review (EC-JRC, 2012). The *resource and emissions profile* is analogous to the LCI phase in product LCA studies. Below, the reporting parts of work packages (5) and (6) are disregarded as the CBC method does not aim to serve external reporting purposes.

(1-2) Goal and scope definition

During goal and scope definition i.a. the targeted audience, intended application as well as system boundaries which consist of organisational and organisation environmental footprint boundaries need to be defined. The organisational boundary refers to activities directly controlled by the organisation such as generation of electricity and disposal of waste. It should be based on the organisation's product portfolio, i.e. the type and amount of products produced during the reporting period. The reporting period is supposed to be one year. The organisation environmental footprint boundaries are broader including indirect upstream and downstream activities like extraction of raw materials, use and EoL of products, transportation and employee commuting. For this list of activities the GHG Protocol is directly referenced underlining that OEF's life-cycle perspective includes emissions normally disregarded in product LCA studies. Hence, in an OEF study scope 1-3 emissions of an organisation can be included. It is recommended to provide a system boundary graphic. Furthermore, assumptions and limitations of the model as well as data sources have to be described.

(3) Resource use and emissions profile
Compiling elementary flows, like e.g. CO_2 emissions, according to the system boundaries is performed in a top-down approach. Flows are weighted and summarised based on the reporting year's product portfolio composition and size. In the guidance document no disaggregation of data flows into different corporate entities or markets is referred to. The OEF model is rather described as a single homogeneous model that can only be disaggregated on product level after its finalisation and based on allocation keys. For example, Martinez et al. (2018a) and Martinez et al. (2018b) used a multiregional input-output approach based on the companies' expenditure data. Neppach et al. (2017) used Material Flow Analysis (MFA) based on a construction company's EMS and product-specific materials management software to compile the inventory. The developers recommend setting up a data management plan depicting system boundaries, data sources, calculation methodologies, data transmission pathways as well as quality checks. For direct activities specific data sources are proposed whereas indirect activities' data can be calculated using generic data sources such as LCI data banks.

(4) Environmental footprint impact assessment
Classification and Characterisation are obligatory steps for the OEF impact assessment whereas normalisation and weighting are optional. The assessment procedure resembles the one for conducting product LCAs: environmental flows gathered in the "Resource use and emissions profile" are correlated with their respective impact categories. Afterwards, each correlated flow is multiplied by the characterisation factors of the respective impact category.

(5) Interpretation (and reporting)
Interpreting the OEF modelling results includes assessing the robustness of the model by checking its compliance with the goal and scope definition and consistency checks for a coherent application of assumptions and methodological choices throughout the modelling process. After identifying environmental hotspots, the results' uncertainties can be analysed by modelling best- and worst-case scenarios of hotspot processes. When multi-regional input-output models are used to set up the resource and emissions profile, evaluation of hotspots is possible on regional and sectoral level (Martinez et al., 2018a, 2018b). When MFA is used to compile the inventory, evaluation of hotspots is possible on product level (Neppach et al., 2017). Finally, recommendations are formulated while considering inherent limitations of the modelling result's validity.

Evaluation of Organisation Environmental Footprint (OEF)
The OEF method aims at making environmental impact footprinting for organisations and companies accessible. When disregarding the environmental impact assessment part, OEF can be used as a basic model to compile organisation-level carbon emissions data over the life cycle of products and services. It has been tested in different industries such as the retail and construction sectors (Neppach et al., 2017). The summarised evaluation of requirements for the OEF method is provided in Table 21.

OEF is per se not a future-oriented method as it is supposed to assess environmental performances of past years. Modelling future emission scenarios is neither mentioned in the guidance nor in screened case studies. In case OEF is in parts applied as basis for the CBC method, input parameters for the main emission drivers would have to be modifiable to meet the *future-orientation* requirement. In the case studies cited above, information regarding expenditures or material amount and composition of purchased products was directly sourced from the companies' software programs and subsequently converted into elementary flows and environmental impacts. In principle, the reporting flow, i.e. the output of product within the system boundary in the reporting year could be manually modified to simulate future projected demands for these products. Similarly, the processes resp. emission factors used from LCI databanks to calculate e.g. energy supply chain emissions of certain products can be changed in order to perform best- and worst case scenarios. Neppach et al. (2017) mention that it is difficult to compare companies' OEF over reporting years with changing product portfolios. The authors therefore propose to normalise OEFs to e.g. the annual gross turnover. In case of OEMs annual past carbon emissions and modelled future carbon emissions could be normalised to an average company vehicle to deal with changing powertrain compositions of fleets. As such, next to information on absolute carbon emissions dependent mainly on the number of sold vehicles, a relative figure is produced which facilitates comparison of carbon performances over the years at the vehicle level. The OEF method does not offer the possibility to simulate product portfolio compositions in line with legislative requirements such as fleet emission averages. OEF therefore meets only partly meets the *future-orientation* requirement.

Requirement *scope 1-3* is met by OEF methodology. In the resource and emissions profile environmental flows like GHG emissions are compiled for the standard product LCA scope including manufacturing, use and EoL phases of products. Furthermore, the OEF boundaries include indirect upstream and downstream activities in line with scopes 1-3 of the GHG protocol. In the OEF guidance document the requirements for data quality concerning i.a. completeness, relevance, consistency are according to the GHG Protocol (WBCSD and WRI, 2004).

The OEF method does not include a feature of relating past and future absolute carbon emissions to a specific carbon budget. As stated before, OEF was not developed as a scenario-building tool but is meant to evaluate an organisations past environmental performance. Though input parameters concerning main emissions drivers like amount of sold vehicles per year could be changed to develop future scenarios, no mechanism exists that relates certain emissions or impacts to a fixed budget. Neither can absolute emission pathways be interpolated between two modelling points in case the model's input data is not readily available for each year. In conclusion, it is possible to use the basic OEF model to compute future emission scenarios though each year's model would have to be specifically built and modelled. The OEF therefore only partly meets the *carbon budget* requirement.

Requirement *reduction measures* demands from screened methods to provide the possibility of remodelling hotspot processes below vehicle level. In the three analysed case studies, the OEF inventories were not based on weighted and aggregated product LCAs but primary accounting and purchasing data was used to create elementary flows (Martinez et al., 2018a, 2018b; Neppach et al., 2017). Accordingly, it is stated in the guidance document that OEF practitioners do not have to be LCA experts. In case the OEF inventory is based on monetary information, modelling of reduction measures is not possible as expenditure flows do not depict the carbon saving potential of one specifically manufactured component over another. On the contrary, carbon-efficient processes or components could be more expensive than their regular counterparts. In case the inventory is based on MFA and product-specific purchased materials, scenarios involving different types and amounts of materials could be built. However, as no LCA models for different products are used as inventory basis, no sub-modules can be evaluated and modelled separately and subsequently extrapolated to company respectively fleet levels. For example, quantifying the impact of using renewable energy for LIBs used in vehicle clusters BEVs and PHEVs is impossible in the OEF methodology. Hence, the *reduction measures* requirement is not met
Though the OEF approach is suitable for companies providing both products and services, it is not specifically tailored to OEMs. Furthermore, it not a future-oriented method so that answering the question how demand for mobility services will impact OEMs' fleets in the future is outside the scoping of the OEF method. In case an OEM's past emissions are computed arising over the life cycle of sold vehicles and offered mobility services, information on amount of produced and used vehicles is available, i.e. no conversion of mobility service demand in needed number of vehicles is needed. This conversion calculation would have to be performed a priori so that resulting numbers of vehicles per market and powertrain could be manually imported into the OEF model. As information on future demand for mobility services cannot be integrated in the OEF method, the *mobility services* requirement is not met.
Direct activities included in the organisational boundary are supposed to be simulated with specific data originating from e.g. corporate EMS. This data flow resembles OEMs' approaches for the calculation of past scope 1-2 emissions as reported to CDP. Indirect upstream and downstream activities contained in

the broader OEF boundary resemble scope 3 categories according to GHG Protocol and can be based on generic data sources. Although neither explicitly stated in the guidance document nor applied in the screened case studies, product LCAs could be used as basis for calculating indirect upstream activities like material supply chains and downstream activities like EoL of products as done by OEM in their carbon accounting. Moreover, data sources and calculations used for calculating other “irrelevant” scope 3 categories used by OEMs can also be used in the OEF methodology. The OEF developers recommend developing use-stage modelling scenarios for assessed products. Computing emissions arising during the use phase separately and based on different data sources than e.g. material supply chain emissions is common practice in OEMs’ carbon accounting. In the guidance it is proposed to use the products’ actual use patterns which can be dependent on national guidelines. When transferring this general recommendation to OEMs, it resembles their approach on calculating sold vehicles’ use phase emissions based on market-specific fleet averages reported to the authorities. As product LCAs could be used to calculate scope 3 cat. 1 and 12 emissions, use phase emissions can be calculated in a separate module of the OEF model, EMS data is used for scope 1-2 emissions calculations and other scope 3 categories can be calculated based on generic data sources already used by OEMs, the OEF method fully complies with the *compatibility* requirement.

The OEF methodology’s general functioning and data flows are for the most part comprehensibly described. The different work packages are clearly defined and data quality requirements are discussed at length and with references to the GHG Protocol. However, what data sources exactly should be used or are recommended to be used remains ill-defined for indirect upstream and downstream activities (scope 3). The general allowance to use generic data sources for indirect activities such as LCI databases and scientific literature leaves room for different approaches as demonstrated by Martinez et al. (2018b) and Neppach et al. (2017). The degree of complexity in equations is low as all environmental flows are summarised to indicate the amount of emissions etc. needed to provide the inventory of the respective reporting year’s product portfolio. The language used is technical and references to other standards like EU-JRC (2011) and ISO 14064-1 (2006c) are included throughout the guidance document. Furthermore, practitioners are asked to clearly state assumptions and limitations of their models as well as to provide graphical illustrations of their OEF model’s structure. As the required data sources are not comprehensively described resp. defined, requirement *comprehensibility* is only partly met by the OEF method.

OEF is an approach to model emissions resp. environmental impacts of the entire reporting organisation within a top-down approach. As stated in European Commission (2012), the inventory can be disaggregated on product level based on allocation keys. This same approach would be suitable to allocate parts of the inventory to specific brands within the reporting organisation. However, different brands are not modelled on their own, i.e. the different fleet sizes and powertrain compositions are not directly linked to the single brand’s absolute emissions within the model. Such information could only be accessed outside the OEF model and subsequently related to emissions allocated to a specific brand based on allocation keys. Requirement company structure is therefore not met.

Table 21 Summary of evaluation of requirements for OEF.

Meta requirement	Requirement	Evaluation
Methodological quality	Future-orientation	◑
	Scope 1-3	●
	Carbon budget	◑
	Reduction measures	○
	Mobility services	○
Practical applicability	Compatibility	●
	Comprehensibility	◑
	Company structure	○

3.4.3 Modular LCA

Modular LCA studies offer the possibility for resource-efficient scenario-analyses over the life cycle of products. As current carbon accounting of OEMs is mainly based on product LCAs, this approach seems promising to amplify the scenario-building power of the CBC method.

Modular LCA studies are based on connected independent and exchangeable information modules which can cover the same scope and generate the same results as regular LCA studies (Buxmann et al., 2009; Steubing et al., 2016). Single modules are defined as "user-defined life cycle stages" (Steubing et al., 2016, p. 513), i.e. specific parts of a product's life cycle which are seen as vital for the study's results respectively decision factors for e.g. managers (Buxmann et al., 2009; Steubing et al., 2016). "User-defined" does not necessarily refer to the main life cycle stages "manufacturing", "use" and "EoL" but can refer to higher disaggregation levels such as the supply chain of a product's component. The development of modules can be based on a prior regular LCA study pinpointing a product's hotspot emissions or impacts (Jungbluth et al., 2000). Modular LCA approaches are especially suitable for scenario-analyses in a corporate decision-making context as they are tailored towards knowledge requirements of specific actors (Buxmann et al., 2009; Steubing et al., 2016). According to Buxmann et al. (2009) and Steubing et al. (2016) a suitable application for modular LCA approaches are explorative studies seeking to analyse a number of technological choices during e.g. the product development phase.

The modular approach allows for resource-efficient analyses of pre-defined product choices as modules are interchangeable and reusable. Additionally, the connection of single modules provides a transparent and clearly represented structure of the LCA model. As such, modular LCA models can be used by LCA beginners. Buxmann et al. (2009) therefore propose to develop modular LCA models which are running on spreadsheet programs and not inside specific LCA programs. The authors further recommend LCA experts to develop spreadsheet-based models displaying the single modules with interconnections. Modules contain information regarding their determined life cycle coverage and LCI. The LCI can cover elementary flows used for complete LCIAs or can be restricted to carbon emission flows in order to calculate carbon footprints of products (Buxmann et al., 2009). With regards to users' decision options, parameters within the modules can be kept variable to facilitate scenario-analyses. Based on regular LCA studies of electric vehicles, variable parameters acting as decision factors for OEMs could be size of LIBs and specific energy mixes used during their manufacturing. Likewise, Steubing et al. (2016) recommend keeping the use phase electricity source in a modular LCA study of BEVs variable. The interconnected information modules are finally set in relation with the reference flow, i.e. the study's functional unit (Buxmann et al., 2009). Based on these suggestions, Figure 23 shows an exemplified modular LCI model of a BEV.

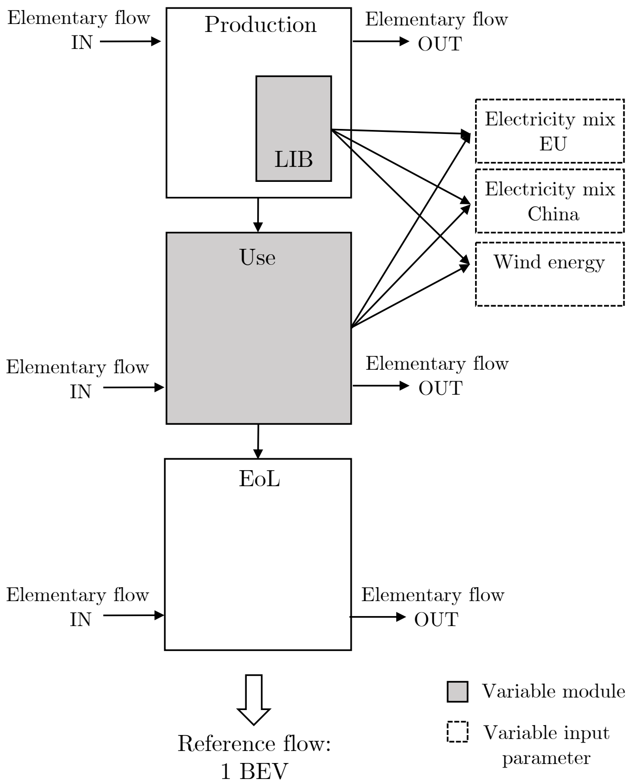


Figure 23 Exemplified structure of a modular LCI model of a BEV. Different energy mixes connected to the LIB production module and the use phase module allow for fast scenario analysis.

Buxmann et al. (2009) additionally suggest to develop variable input parameters based on user-specific "what if"-scenarios. An exemplified question could be: "What is the impact on the product's overall carbon footprint if we manage to lower the cobalt content by X% in the LIB?". Due to this simplified LCA approach, non-LCA experts like product designers or managers can derive conclusion without constant support of the model's developers. Only if new questions arise LCA experts are needed to set up new modules and connections.

The modular LCA approach described above can be based on the modularity principle proclaimed by ISO 14025 (ISO, 2006d) for type III environmental product declarations (EPD) (Buxmann et al., 2009). EPDs describe pre-determined environmental aspects of products. Different information modules (IM) gather data relating to single processes or combination of processes over the life cycle of the assessed product. The IMs are connected and scaled in relation with the reference flow. According to the authors, a modular LCA model based on such IMs is generally operating as prescribed by ISO 14044.

Evaluation of modular LCA approaches

The modular LCA approach described above is applied for product environmental impact assessment and carbon product footprinting, respectively. To the author's knowledge it has not been specifically implemented on organizational scale yet. Although emissions of single modules are calculated separately in the LCI, they are eventually connected to the reference flow. Hence, modular LCA facilitates modelling emissions and impacts arising over a product's life cycle in a holistic way while enabling uncomplicated scenario-analyses on life-cycle phase or single-unit process level. The summarised evaluation of requirements for the modular LCA approach is provided in Table 22.

Albeit being generally suited for scenario-analysis, requirement *future-orientation* specifies the method's need to include OEMs' major emissions drivers. The modular LCA approach allows for extrapolating environmental impacts from one to several equal products via adjusting the reference flow. However, as it has not been used on organisational scale yet, adjusting the reference flow according to changing size and composition of product portfolios is not possible as only one product is assessed at a time. Likewise, calculating portfolio composition in relation to a given market- and time-specific fleet average is not possible. Modular LCA is suitable to keep decision factors resp. technical properties variable which corresponds to scenario-analyses of future CO_2-intensities of electricity mixes. As OEMs' upscaling to fleet levels is based on vehicle LCAs, these could be connected to modular energy mixes. As the modular LCA approach described here can incorporate one of the variable emissions drivers, it partly meets the *future-orientation* requirement.

Modular LCA does not meet the *scope 1-3* requirement as it is has been so far only applied on product level. Likewise, requirement *carbon budget* is not met as no emissions time-series are computed. *Reduction measures* requirement is not met by the modular LCA approach as relating product-level reduction measures to portfolio size and composition information is not possible. Though the described modular LCA approach is generally in line with ISO 14044 (Buxmann et al., 2009) and LCA studies can be used to compare life-cycle carbon emissions of private vehicles and mobility services, the product-level modular LCA approach cannot integrate information on future mobility service demand. Therefore, requirement *mobility services* is not met.

As the modular approach currently does not cover organisational scales, requirement *compatibility* as well as *company structure* are not met. Especially the modular LCA approach by Buxmann et al. (2009) is clearly described. Based the method on ISO 14025 and ensuring compatibility with ISO 14044 shows the model's structure, data sources and data flows being in line with existing standards. The modular LCA approach by Buxmann et al. (2009) is low in complexity as it is tailored towards being used by non-LCA experts. The approach therefore meets requirement *comprehensibility*.

Table 22 Evaluation of requirements for the modular LCA approach.

Meta requirement	Requirement	Evaluation
Methodological quality	Future-orientation	◑
	Scope 1-3	○
	Carbon budget	○
	Reduction measures	○
	Mobility services	○
Practical applicability	Compatibility	○
	Comprehensibility	●
	Company structure	○

3.4.4 Road transport emission models

OEMs' past carbon accounting is market-specific with the number of vehicles sold worldwide being the main factor influencing absolute emissions (see 2.3). Therefore, models simulating future carbon emissions arising from road transport on country or global level are considered. Based on the classification by Linton et al. (2015), only macro-scale and long-term methods computing emissions from road transport are analysed in the following. These approaches are used to simulate emissions of the transport sector on different geographical and temporal scales thus not being specifically directed at OEMs. The CBC method does not aim at projecting future mobility or vehicle demand itself but nonetheless needs to be able to integrate existing projections on demand for vehicles and mobility service into OEMs' projections on composition and size of fleets. The focus is therefore laid on the models' structure and data flows to compute emission time-series as well as their outputs. In the subsequent sub-chapter, the described approaches are assessed for their ability to meet the requirements posed on the CBC method.

Techno-economic models combine technology-related, economic as well as socio-economic data (Linton et al., 2015). So-called E3 models form part of this category dealing with energy, economic and environmental data to simulate future emission pathways (Linton et al., 2015; Schäfer, 2012). Generally, these models focus on technology- rather than behavioural-facilitated change (Linton et al., 2015). An example is the *Global Transportation Energy and Climate Roadmap* by the International Council for Clean Transportation (ICCT) (ICCT, 2012; Linton et al., 2015). The underlying techno-economic model simulates transport-sector emissions from 2000 to 2050 in five-year steps with a focus on high-vehicle-selling regions such as the US, EU and China (ICCT, 2012). Time- and region-specific vehicle activity (v-km) is related to i.a. caused WTW GHG emissions. Transport modes include LDVs, Heavy-Duty Vehicles (HDVs) and buses with different powertrains such as ICEs, PHEVs and BEVs. Similar to Schäfer and Victor (2000), the main socio-economic parameters influencing personal mobility demand and thus demand for vehicles in the ICCT Roadmap model are GDP growth, population growth and transportation cost (e.g. fuel prices) (ICCT, 2012). The structure and data flows of this techno-economic model are exemplarily shown for LDVs in Figure 24.

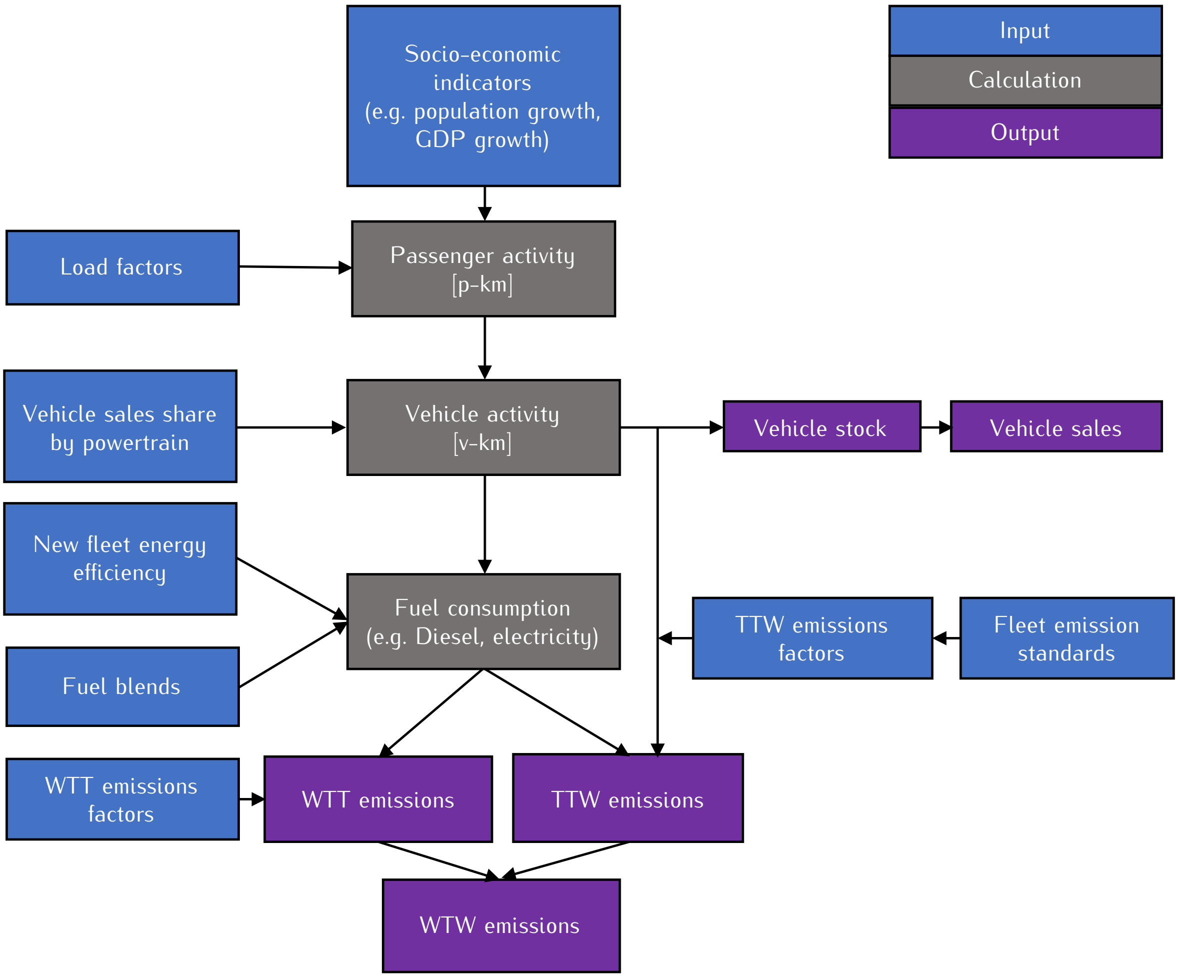


Figure 24 Techno-economic model of the ICCT Roadmap exemplarily focusing on LDVs. Arrows indicate data flows. Based on ICCT (2012).

Based on socio-economic parameters, passenger activity, i.e. demand for personal motorised mobility (expressed in p-km) of a specific transport mode is computed. In the following, load factors are used to determine vehicle activity (expressed in v-km) and finally vehicle stock and sales. Although not explicitly stated in the ICCT Roadmap, the underlying calculations are likely to be based on Schäfer and Victor (2000).

The authors state that based on projected p-km of passenger cars (PKM) motorization rates respectively the needed number of passenger vehicles ($n_{veh,abs}$) can be calculated via dividing PKM by the respective load factors (lf) and amount of v-km travelled per LDV (VKM_{veh}):

$$n_{veh,abs} = \left(\frac{PKM}{lf}\right) * (VKM_{veh})^{-1}$$

(3.1)

Additionally, in the ICCT Roadmap model demand for LDV (LDV_d) is divided into demand for vehicles with different powertrains by correlating it with projected demand for powertrain shares (ICCT, 2012). Country- or region-specific fleet averages are used to calculate TTW emissions via TTW emission factors. WTT emissions are computed as a product of fuel consumptions of different vehicle types and WTT emission factors. In the end, WTT and TTW emissions are summarised to WTW emissions. In the ICCT model, no rebound effects arising from e.g. improved fuel efficiencies are considered as their quantification on such aggregated geographic scales is too unreliable (ICCT, 2012). Input parameters as e.g. powertrain shares and load factors can be changed within such techno-economic models to compute the respective impact on WTW emissions (Linton et al., 2015).

Where the ICCT model is lacking data, IEA's Mobility Model (MoMo) is consulted (ICCT, 2012). As stated in 2.2.3, the MoMo database is used by SBTi in its transport sector tool to compute OEMs' carbon emission pathways (WWF, 2019). It is also used as a source for IEA's *Energy Technology Perspectives* and *World Energy Outlook* (IEA, 2019a). As the MoMo database is not open source, the model's underlying equations and assumptions are not entirely published. Still, Fulton et al. (2009) provide an overview of IEA's MoMo which is summarised in the following. Similar to the ICCT approach, the MoMo database is a techno-economic model projecting global transport sector GHG emissions, energy demand and pollutants until 2050 in 5-year timesteps (Fulton et al., 2009; IEA, 2014b). In the road transport module, LDVs, HDVs and buses with e.g. ICE, PHEV, BEV and CNG powertrains are included (Fulton et al., 2009). Based on historic data, the MoMo database can also be used to model past transport sector emissions dating back to 1975 (Fulton et al., 2009; IEA, 2020). Main techno-economic variables influencing vehicle demand and thus GHG emissions include developments of GDPs, population, taxes and fuel prices. In the MoMo database, region-specific GHG emissions caused by passenger road transport (G) are computed by applying the ASIF equation (Fulton et al., 2009). A stands for activity in p-km, S represents the structure of modelled transport i.e. load factors of different transport modes, I depicts the energy intensity of used fuel types and F represents emission factors for each fuel type. The total emissions are summarised for the included modes (m), e.g. private vehicles, and fuel types (f), e.g. Diesel (Schipper et al., 2000).

$$G = \sum_{modes} \sum_{fuels} A_{m,f} S_{m,f} I_{m,f} F_{m,f} \tag{3.2}$$

In contrast to the ICCT model, the scope of emissions covered includes material supply chain emissions of projected vehicle demand next to WTW emissions. How exactly these emissions are calculated remains unclear as the documentation is not available. In this context, the authors claim to model life-cycle GHG emissions of demanded vehicles although emissions arising from vehicles' EoL phase do not seem to be included. Furthermore, although policy variables such as fuel taxes are considered, future legislations on fleet averages do not seem to be used as input variable. The MoMo database is developed in MS Excel which facilitates "what-if" scenario-building as input parameters can be changed (Fulton et al., 2009). For example, scenarios can be modelled to analyse the impact of changing modal splits on total GHG emissions (IEA, 2014b) allowing specific questions such as: "What is the impact on total GHG emission in China if mobility demand for buses rose by 20%?".

Evaluation of road passenger transport simulations

The techno-economic models described above are both facilitating the analysis of macro patterns in transport-sector emissions. Main addressees are therefore policy-makers deciding on region-specific CO_2-reduction measures in freight and passenger transport (Linton et al., 2015). OEMs are not directly addressed within the models or guidance documents. However, IEA's MoMo is already used by OEMs striving to support the Paris Agreement as it delivers the basis for Paris Agreement-compatible emissions calculations in SBTi's methodology. In the following, the two models are assessed for their ability to meet the CBC method requirements. Although the models slightly differ in their structure and outputs, they are evaluated simultaneously. Table 23 provides an overview of the evaluation. Techno-economic models are not yet integrated in organisation-level CO_2-emissions modelling. Therefore, the requirements developed for the CBC method are only partially or not met at all by the assessed models. The following evaluation is hence performed to find potentials for combining OEMs' carbon accounting approaches with projections on future mobility demand.

Requirement *future-orientation* demands suitable approaches to provide variable input parameters for OEMs' main emission drivers. As techno-economic models are not analysing emissions on organisational scale, *future-orientation* is not met. Nonetheless, the models give insights on how future emissions of the transport sector are modelled based on past emissions. The MoMo uses back-casting to validate and calibrate the model for emission projections, i.e. as aimed for in the CBC method, an established data basis is linked to modifiable parameters resulting in future emission projections. For example in the ICCT model, forecasted vehicle activity is linked to varying load factors and shares of powertrains to determine annual region-specific vehicle stocks and sales. Subsequently, varying time- and region-specific fleet averages are linked to vehicles sales to calculate TTW emissions. As such, modelling future WTW resp. WTW and production phase emission scenarios arising from sold LDVs is possible within a holistic approach.

Neither scope 1-3 emissions according to the GHG Protocol nor life-cycle carbon emissions of sold products are covered by techno-economic models. Therefore, the assessed road transport emission models do not meet requirement *scope 1-3*. The assessed techno-economic models are used to compute future emission time-series in 5-year timesteps. However, neither are emission projected at the group or brand level nor are annual emissions summarised and set in relation to a carbon budget. Hence, requirements *carbon budget* and *company structure* are not met.

Requirement *reduction measures* is not met by techno-economic models as measures at the vehicle level cannot be extrapolated to company-fleet level. Both in the ICCT and the IEA model, scenario-analysis including reduction measures is possible on regional level. For example, powertrain shares and electricity mixes can be modified and their impact analysed. Although in the MoMo production phase emissions are included, it cannot be evaluated in how far reduction measures at the vehicle level can be modelled. It remains unclear whether or how emissions arising from manufacturing are based on vehicle LCAs. Information on scenario-building capacity are only related to use phase emission modelling. As mobility services are not included in the assessed models, the impact of mobility services on OEMs' fleet size and composition cannot be quantified. Requirement *mobility services* is not met. Nonetheless, the models offer insight on how available projections of vehicle demand can be used to integrate mobility service demand in OEMs' emission modelling.

Neither the ICCT nor the IEA model use data sources and flows compatible to OEMs' carbon accounting. Requirement *compatibility* is thus not met. Still, use phase emission calculation of LDVs is similarly structured to scope 3 cat. 11 calculations of OEMs: based on region-specific fleet emission averages and number of sold vehicles absolute TTW emissions are derived via CO_2 emission factors. WTT emissions are calculated separately and subsequently summarised with TTW emissions to absolute WTW emissions. A major difference between the scope of techno-economic models and OEMs' carbon accounting is that both sold vehicles and vehicle stock are analysed. This approach entails that each year only annual WTW emissions of sold and existing stock vehicles are depicted. In the case of IEA's MoMo, it is possible that production phase emissions are equally assigned over LDVs' modelled lifetime. In OEMs' carbon accounting vehicle stocks do not need to be accounted for as each year life-cycle emissions of sold vehicles are calculated and reported. In order for the CBC method to provide future-oriented carbon accounting for OEMs which is compatible with existing approaches, modelled future emissions of sold vehicles have to cover the whole life cycle each year as well.

Although the main structure of both the ICCT and IEA model is comprehensible as depicted in Figure 24, the exact input parameters are not publicly documented. As mentioned above, it remains unclear how LDVs' production phase emissions are modelled and which WTT and TTW emission factor are applied. The degree of complexity in equations can only partly be assessed as e.g. the exact correlations of developments in GDP, population growth etc. and mobility demand are not documented to the author's knowledge. Though parts of the models that are well described and summarised above are precisely described. Therefore, the assessed road transport emission models partly meet the *comprehensibility* requirement.

Table 23 Evaluation of requirements for road transport emission models.

Meta requirement	Requirement	Evaluation
Methodological quality	Future-orientation	○
	Scope 1-3	○
	Carbon budget	○
	Reduction measures	○
	Mobility services	○
Practical applicability	Compatibility	○
	Comprehensibility	◑
	Company structure	○

3.5 Summary of method development

Based on the developed methodological and practical requirements of the CBC method, additional approaches outside the corporate carbon management research field were assessed. First, the O-LCA and the OEF were evaluated representing methods applied to calculate CO_2 emissions on company-level. Second, the non-company level approaches, modular LCA as well as macro-scale and long-term road transport emissions models were evaluated due to their promising characteristics for meeting several of the requirements. In the following, characteristics of the evaluated methods which are useful for the subsequent development of the CBC method are summarised. The summary is structured following the eight requirements. An overview of the evaluation results is provided in Table 24.

Future-orientation

None of the assessed methods fully meets the *future-orientation* requirement. In both the O-LCA and the OEF approaches, however, scenario analyses are generally possible. For instance, by manually changing time-specific input parameters, emissions caused in different years can be modelled. This facilitates the use of, for example, projected vehicle sales as input parameter to analyse future emission scenarios. The O-LCA uses cluster product LCAs representing e.g. vehicles with different powertrains which are weighted according to the reference year's product portfolio. Changing decisive input parameters such as CO_2-intensities of electricity mixes cannot be uniformly modified for respective product clusters. As such, for every year new cluster LCAs would have to be produced.

Scope 1-3

As both OEF and O-LCA use the GHG Protocol as accounting standards they fully meet requirement *scope 1-3*.

Carbon budget

It is theoretically possible to manually add up calculated emissions of several years because company-level scope 1-3 emissions can be calculated in the O-LCA and the OEF. The assessed road transport emission models do not fulfil this requirement but show that linearly interpolating between future modelling points is a feasible approach to deal with data gaps.

Reduction measures

The O-LCA can be used to quantify reduction measures on product level and extrapolate the effect to company level according to the composition and size of the product portfolio. However, in order to model the effect of reduction measures on scope 1-3 emissions, new cluster vehicle LCAs would need to be produced. Likewise, it is not possible to model reduction measures for specific timespans only, as within the O-LCA only one timespan with a fixed set of input parameters can be modelled at a time. Modular LCA approaches are, so far, only implemented on product level. The connection of modularised LCA computation to fleet level input parameters for different modelling points (i.e. years) is thus not yet possible.

Mobility services

The requirement of *mobility services* is the only requirement that is entirely unfulfilled by the assessed methods as none of them are specifically directed at OEMs. Consistent with Burritt et al. (2011), the necessity of developing sector-specific carbon management approaches is highlighted. The road transport emission models offer insight on the utility of available projections of vehicle demand for integrating mobility service demand in OEMs' emission modelling. First, in the ICCT model, the overall demand for personal motorised mobility is computed in p-km. Second, load factors and vehicle lifetime kilometrage are used to determine the number of demanded vehicles. However, no method currently exists to combine the market-specific forecasted amounts of p-km with OEM-specific scope 1-3 emissions modelling for fleets consisting of both private and service vehicles.

Compatibility

The OEF shows a high level of compatibility with OEMs' past emissions reporting whereas the O-LCA is only partly compatible. The road transport emissions models and the modular LCA do not meet the requirement. Both the OEF and the O-LCA approaches allow for vehicle LCAs to be used for supply chain and recycling emissions reporting. Moreover, EMS data can be sourced for scope 1-2 emissions reporting and accompanying scope 3 categories be calculated based on generic data sources. The distinction between the scores of OEF's and O-LCA is that regionalised use phase emission calculation based on national guidelines is recommended in the OEF handbook. This approach corresponds with OEMs' market-specific fleet emissions reporting and subsequent calculation of WTW emissions.

Comprehensibility

The modular LCA and the O-LCA score highest for the *comprehensibility* requirement as the methods are clearly structured along specific ISO standards. OEF and O-LCA adapt the product LCA working phases to company level emissions calculation. Other than the techno-economic models, all approaches use a low degree of complexity in equations which are clearly described. A continuous use of explanatory diagrams supports understanding data sources and flows. In accordance with product LCA studies, goal and scope as well as stating limitations of analyses are required.

Company structure

In the O-LCA handbook the integration of different brands into a company's carbon footprint is clearly described. Emissions of different brands with similar products are calculated separately as brands differ in their specific portfolio composition but are all based on the same cluster LCAs. In case of an OEM, only the fleet perspective between brands differs, while data sources at the vehicle level are the same for every brand. The other assessed approaches do not meet this requirement.

Overall evaluation scores of analysed methods and requirements

Both the single methods' ability to meet all requirements as well as the extent to which each requirement is met by all methods is summarised in Table 24. In order to make evaluation results of the different methods and requirements comparable, a simple scoring system is used.

For the method perspective, the eight established requirements are evaluated and therefore the score ranges from 0 to 8. If a requirement is fully met, 1.0 is scored, if it is only partially met 0.5 is scored, and if a requirement is not met at all the score is 0. Finally, the single scores for each requirement are summed resulting in the total score. This scoring approach facilitates the identification of the most suitable method to base the CBC method upon. The O-LCA scores the highest number of points (5 points), followed by the OEF (3.5 points), then the modular LCA (1.5 points), and then the road transport emissions models (0.5 points).

For the requirement perspective, the score ranges from 0 to 1 as the requirements can either be fully met by a method (score 1), partially met (score 0.5) or not met at all (score 0). Rather than a summation of the requirement scores, the highest score achieved among the methods was instead identified. This scoring approach facilitates the identification of missing elements that need to be newly developed in order for the CBC method to meet all requirements. Therefore, the methodological basis of the requirements that do not score 1 need to be amended by the author either by combining the suitable elements of different methods or by developing new methodological elements. The requirements *scope 1-3*, *compatibility*, *comprehensibility*, and *company structure* score 1 each. The requirements *future-orientation*, *carbon budget*, and *reduction measures* score 0.5 each and the requirement *mobility services* scores 0.

Table 24 Evaluation scores of the analysed methods and requirements.

Requirement	**Evaluation**				**Requirement score (0-1)**
	Organisational Life Cycle Assessment (O-LCA)	Organisation Environmental Footprint (OEF)	Modular LCA	Road transport emission models	
Future-orientation	◑	◑	◑	○	0.5
Scope 1-3	●	●	○	○	1
Carbon budget	◑	◑	○	○	0.5
Reduction measures	◑	○	○	○	0.5
Mobility services	○	○	○	○	0
Compatibility	◑	●	○	○	1
Comprehensibility	●	◑	●	◑	1
Company structure	●	○	○	○	1
Method score (0-8)	5	3.5	1.5	0.5	

3.6 Discussion of method development

The summary of method screening and evaluation above shows that none of the assessed approaches meets all necessary requirements to achieve the research objective. Further, some of the requirements were not fully met by any of the assessed methods. This finding supports the tentative conclusion in the initial deficit analysis (see 2.5) that so far no method exists to facilitate computing OEMs' carbon emissions over the life cycle of vehicles and mobility services in relation to a carbon budget. In this section, it is thus discussed which additional elements need to be developed in order for the CBC method to have all necessary characteristics. Again, the analysis is structured following the eight requirements. An overview of existing elements and elements to be developed in this dissertation is provided in Figure 26. Additionally, it is analysed whether one of the evaluated approaches can function as the main structural basis for the CBC method and, if so, which one is most adequate. Based on the results of this section, the CBC method is derived in the next chapter.

Future-orientation
The O-LCA, OEF and modular LCA approaches each contain suitable elements to be combined within the CBC method. However, a holistic scenario-analysis approach is missing: none of the methods facilitates scenario-analyses over a timespan of several years in which time-specific input parameters can be adjusted. Furthermore, an integrating element is missing which allows for future scenario-analyses to be based on past reported emissions.

The O-LCA provides a suitable basis for the CBC method as it uses cluster-LCAs as a practical solution to model diverse product portfolios which change over time. It can be combined with the OEF's approach to regionally model use phase emissions. Here, a fleet emissions calculator needs to be added in order to check whether assumed powertrain and vehicle size compositions on fleet level meet future legislative requirements. The modular LCA approach can be combined with the O-LCA's cluster LCAs and OEF's regionalised use phase emissions. In this manner, region-, time- and market-specific carbon intensities of hotspots such as the LIB production and well-to-wheel use phase emissions caused by ICEs and electrified vehicles can be modelled. Even new markets could be added modularly. If in the future India, for example, becomes an important market, the Indian fleet could also be modelled based on cluster-LCAs with a regionalised assessment of use phase emissions and LIB production.

Though, in general, specifications for scenario development are missing. A process to be followed for scenario development within the CBC method should therefore be specified and added to the method description in order to facilitate the correct application of the CBC method (see requirement *comprehensibility*).

Scope 1-3
This requirement is fully met by both the O-LCA and OEF. Past reported scope 1-3 emissions serve as the basis for future emissions modelling. The computation of past and future scope 1-3 emissions therefore needs to be holistically included in the CBC method. This includes reported carbon emissions caused by the analysed main emission drivers. These need to be calculated in the CBC method to compute future emissions in the same manner. In order to model resource-efficiently, full compatibility with existing reporting data systems needs to be ensured. The additional element to be developed for the CBC method is thus facilitating the computation of hotspot scope 1-3 category emissions and inclusion of all scope 1-3 emissions categories within one model.

Carbon budget
The prerequisite to analyse a scenario's total emissions in relation to a Paris Agreement-compatible carbon budget is to compute a company's scope 1-3 emissions over several years within one method. As already discussed for the requirement of *future-orientation*, scope 1-3 emissions computed in the O-LCA or OEF would have to be manually summed in order to derive the amount of total carbon emissions caused over several years in a specific scenario, i.e. the parenthesis covering timespans longer than a year is missing. The evaluation of the road transport emission models showed that data gaps are likely in future long-term emissions modelling. Therefore, the linear interpolation between specifically modelled years as applied in the road transport emission models should be included in the CBC method. Additionally, the automated calculation of distance-to-target between the modelled emissions and the carbon budget needs to be developed.

Reduction measures
Similarly to *future-orientation*, a modular approach to modelling reduction measures needs to be combined with the O-LCA method. For example, calculating material supply chain emissions must not be fixed within cluster-LCAs but needs to be modularised. Carbon hotspots, like the production of LIBs, should be modelled separately in order to facilitate computing scenarios such as with a modified energy source. Similar to the cluster-LCAs, these modules need to be related to corresponding parameters on fleet level, i.e. in this case the number of BEVs and PHEVs for which the measure should be operationalised. Equally to the proposed modular use phase emission calculation for *future-orientation*, reduction measures tackling a whole life-cycle phase should be modularised. For example, modelling the use of biofuels instead of conventional fuels in a certain market is only possible if use phase emissions of different powertrains are calculated separately and in a market-specific manner.

Hence, a modular life-cycle approach (based on the assessed modular LCA) needs to be combined with O-LCA's cluster LCA approach. In other words, as a newly developed element, the life-cycle phases "production", "use" and "end-of-life" are modelled separately but are connected to respective fleet level input parameters such as the number of BEVs. Within these life-cycle phase modules, sub-modules for carbon hotspots should also be separately calculated. Like this, reduction measures can be modelled brand-, market- and time-specifically on fleet level within CBC method.

Mobility services

Mobility service vehicles differ from private vehicles in their use patterns and thus in their life-cycle CO_2 emissions when using p-km as the reference unit due to i.e. differing load factors (see 2.4). Though, regardless of whether a vehicle is offering a service or is used by private owners only, it causes carbon emissions during its production, use, and end-of-life as well as, from the company perspective, in other scope 3 emissions categories (like e.g. business travel). Vehicles produced by the OEM which are used for offering any mobility service (car sharing, ride hailing, ride pooling) can thus be treated equally to privately used vehicles from a past-emissions-reporting perspective: cluster-LCAs can be used for material supply chain and end-of-life emissions calculation; environmental information systems' data can be used for scope 1-2 emissions reporting; fleet emission averages and electricity consumptions can be used for well-to-wheel emissions calculation; and generic data sources can be used for scope 3 other categories calculation. From the past-emissions reporting perspective even the use phase emissions can be treated equally to those of private vehicles when assuming that the lifetime vehicle kilometrage (150,000-200,000 v-km) is the same for private and service vehicles (see 2.2.1 for OEMs' carbon accounting methodology). This is the case because the vehicles' capacity to be driven for a certain distance during its lifetime is not necessarily affected by the mode of transport it is offering. Likewise, from the reporting perspective it does not matter that service vehicles "deplete" their lifetime v-km faster than private vehicles (due to the higher capacity utilisation) as the life-cycle carbon emissions of every produced vehicles is accounted for in one reporting year.

In order to make the computation of an OEM's future scope 1-3 emissions comparable to past reported emissions, the same lifetime kilometrage must be assumed. So how will the inclusion of mobility services in an OEM's portfolio become noticeable in the modelled future absolute CO_2 emissions? First of all, the service vehicles will affect the size of the OEM's fleet, i.e. the number of vehicles needed to satisfy the projected p-km demand. This effect is due to some service vehicles having higher average load factors than private vehicles and thus provide a higher amount of lifetime p-km (see 2.3.1). Therefore, amounts of market and time-specific p-km projected by road transport emissions models that are already used by e.g. the SBTi for their target-setting methodology can also be used as input for the CBC method. The projected demand of motorised personal p-km can be split up in p-km demand for private vehicles and different mobility services via shares of projected demand for different mobility services. Next, load factors of mobility services determine the number of required vehicles to satisfy the p-km demand. Additionally, available lifetime vehicle-km of ride hailing and pooling services need to be adjusted for empty travels (see 2.3.1). Secondly, the inclusion of service vehicles will affect the overall powertrain and vehicle size composition of the OEM's fleet as service vehicles are partly bigger and heavier (ride pooling) and might be electrified to higher shares than average private vehicles. It is thus necessary to compute life cycle emissions for service vehicles in the same manner as for private vehicles in order to show these effects on fleet level. The general approach to model the effect of future mobility service demand on vehicle fleet size is shown in Figure 25. The OEM-specific approach that includes the calculation of life-cycle carbon emissions is developed in the next chapter.

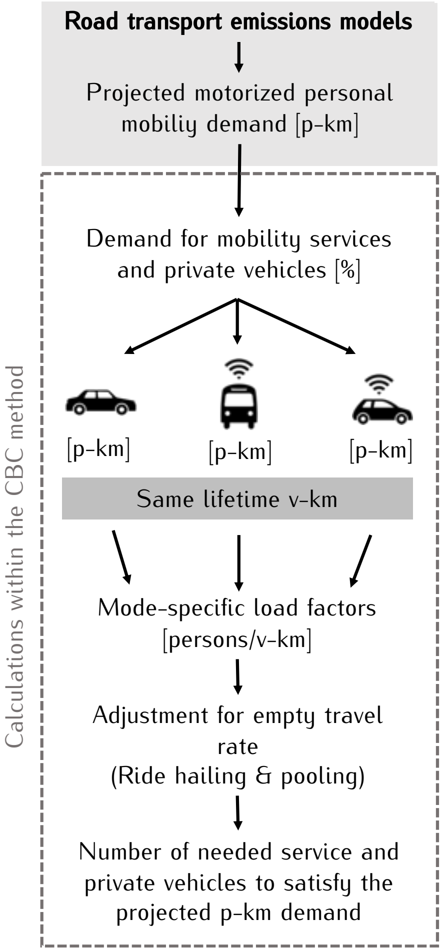


Figure 25 Proposed general approach to model the effect of future mobility service demand on vehicle fleet size.

Compatibility

This requirement is entirely met by the OEF. It facilitates the calculation of company scope 1-3 emissions according to the data sources used by the OEMs. Regionalised use phase assessment is possible by using market-specific fleet emissions averages. Therefore, no new element needs to be developed.

Comprehensibility

This requirement is completely met by two of the assessed methods. It is, however, necessary to discuss which comprehensible structure should be used in the subsequent method derivation chapter. With a transparent description of assumptions, data sources, equations etc., the method's credibility is strengthened among corporate decision-makers and is more likely to be applied (Schwegler et al., 2011). It is thus vital for the CBC method to be comprehensible for both practitioners and decision-makers. The evaluated methods based mostly on the LCA methodology (O-LCA and modular LCA) score highest for *comprehensibility*. In addition to the O-LCA and modular LCA, the OEF also demands clear descriptions of the assessed scenarios such as geographical and temporal scope as well as assumptions and data sources in line with the LCA methodology's "goal and scope definition" phase. In general, the clear language, understandable formulas, and explanatory diagrams used by the O-LCA, the modular LCA, and the OEF should be used in the CBC method derivation.

The guiding document for the scope of emissions covered in the CBC method is the GHG protocol which takes on an "LCA^+ perspective". It covers the life-cycle phases according to the LCA methodology as well as other scope 3 categories like commuting which are not part of standard product LCA studies. Furthermore, the LCA-based methodology O-LCA has the highest score regarding the meeting of requirements of all the assessed methodologies. The LCA methodology with its distinction in life-cycle phases, transparent description of goal and scope of the analysis and of modes of calculation should thus be used as the basic structural element for the CBC method. As such, in the method derivation chapter, first, the general calculation method of company-level carbon emissions per life-cycle phase should be clearly described. Next, those requirements that need specific calculations and concern all life-cycle phases should be specified. This applies to the requirements *reduction measures*, *mobility services*, and *carbon budget*. The required steps to develop the scenarios that will be modelled within the CBC method should be delineated after the necessary calculations of the CBC method as the “modelling instrument” are described.

Company structure
This requirement is completely met by the O-LCA. Within the CBC method, the brand-specific approach described for the O-LCA should therefore be resumed: different brand-specific input parameters such as powertrain shares or vehicles size shares are connected to the same cluster vehicle LCAs.

Overview and origin of the CBC method’s elements
Based on the above discussion, the existing and new elements of the CBC method are shown in Figure 26. Following the development of the currently missing elements, the main effort of the following chapter is to integrate all listed elements within the CBC method and to coherently describe its mode of calculation as well as its application.

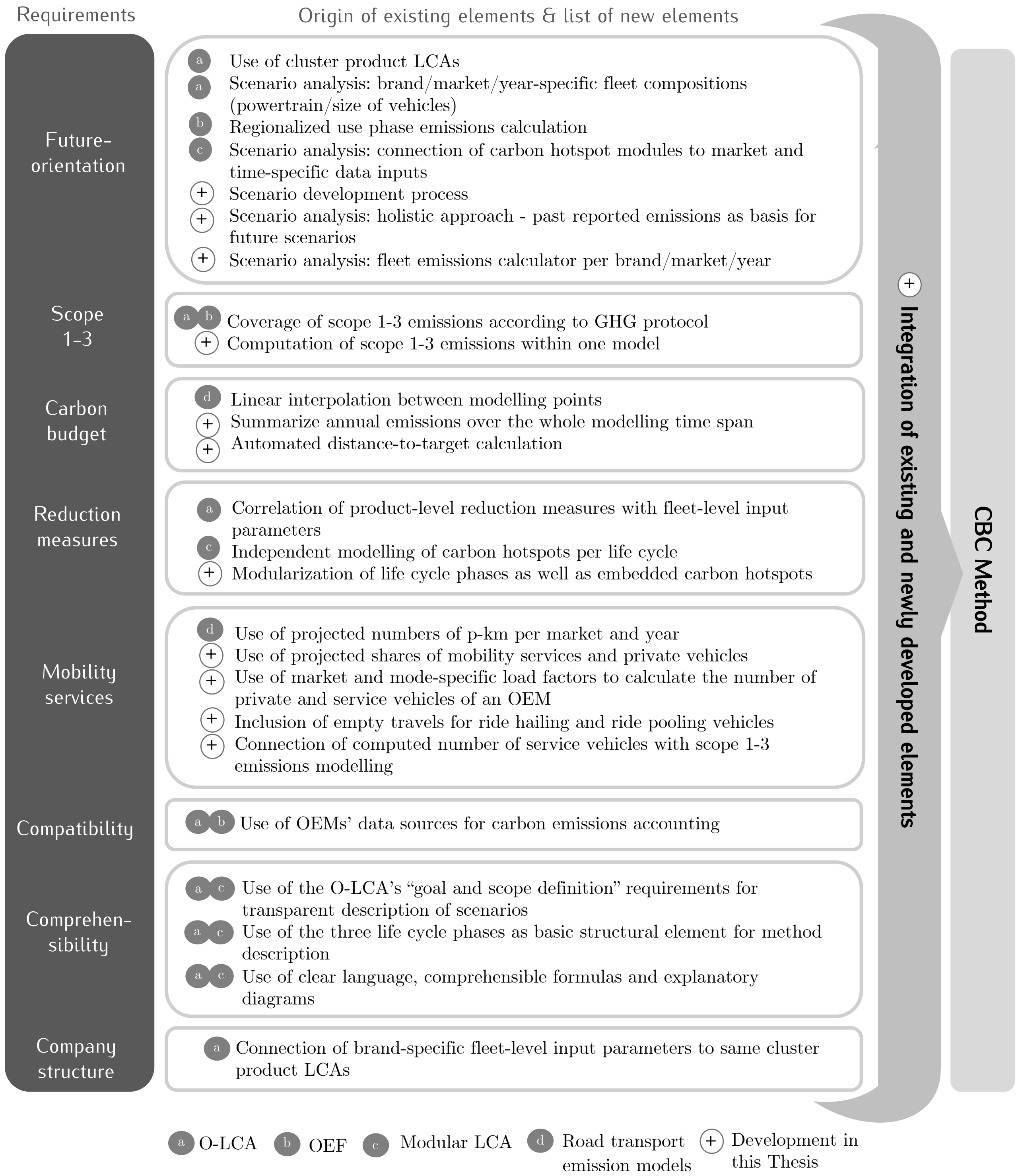


Figure 26 Overview and origin of the CBC method's elements.

4 Method derivation

In order to answer sub-research question 4 ("How can practical and methodological requirements be integrated in one modelling method?") the CBC method's mode of calculation is derived based on the implications developed above (3). First, the calculation methods for company-level emissions per life cycle phase are described. Next, calculation methods for requirements that address carbon emissions in all life cycle phases are delineated. A graphical overview of the CBC method's data flows is provided in 4.11. Finally, the application of the CBC method is addressed by describing the procedure to be followed for the scenario development and analysis

4.1 Breakdown of life cycle phases

As modelling of future emissions needs to be based on past reported emissions, the starting year's absolute emissions of an OEM are re-calculated. As such, the accuracy of modelling results can be tested by comparing modelled emissions to reported ones. Though the general mode of calculation for past emissions is in accordance with calculating future absolute emissions. In order to be able to model emission pathways for OEMs' brands separately, absolute emissions ($E_{\text{OEM},abs}$) are disaggregated on brand level ($E1 - \text{En}_{abs}$):

$$E_{\text{OEM},abs} = E1_{abs} + E2_{abs} + En_{abs} \tag{4.1}$$

Brand absolute emissions (E_{abs}) are split up between the three life cycle phases "production" (E_Prod_{abs}), "use" (E_Use_{abs}) and "EoL" (E_EoL_{abs}) as well as remaining scope 3 categories (E_Oth_{abs}) to cover scope 1-3 emissions:

$$E_{abs} = E\_Prod_{abs} + E\_Use_{abs} + E\_EoL_{abs} + E\_Oth_{abs} \tag{4.2}$$

The calculation and data flows for each of the above summands are described below starting with the production phase. Next, reduction measures (4.6), adapting the starting year's data to future years (4.7), the inclusion of mobility services in the fleets (4.8), interpolation between specifically modelled years (4.9) and, finally, carbon budget compliance calculations are described (4.10).

4.2 Production phase

Brands' production phase emissions (E_Prod_{abs}) are distinguished into CO_2 emissions caused in the material supply chains ($E\_Prod\_SC_{abs}$) and scope 1-2 emissions directly controlled by the brand, hereafter called "In-house Production" ($E\_Prod\_InH_{abs}$):

$$E\_Prod_{abs} = E\_Prod\_SC_{abs} + E\_Prod\_InH_{abs} \tag{4.3}$$

The main driver of brands' absolute carbon emissions is the number of vehicles sold. $E\_Prod\_InH_{abs}$ is derived from EMS measuring electricity consumption etc. directly on the production sites. $E\_Prod\_InH_{abs}$ thus depends on scope 1-2 emissions caused per vehicle ($E\_Prod\_InH_{veh}$) and the total number of vehicles sold (n_{veh}):

$$E\_Prod\_InH_{abs} = E\_Prod\_InH_{veh} * n_{veh} \tag{4.4}$$

The amount and type of material used for manufacturing vehicles determine brands' supply chain emissions ($E\_Prod\_SC_{abs}$). I.e. heavier vehicles cause higher CO_2 emissions in their supply chains than lighter ones. To depict differences in brands' product portfolios vehicle curb weights (DIN) are used to distinguish the vehicle segments "regular" (<1.7 t) and "large" (>1.7 t). The powertrain is another factor influencing supply chain CO_2 emissions of a single vehicle and thus also $E\_Prod\_SC_{abs}$. As, to the author's knowledge, no LCA study of a marketable FCEV vehicle is publicly available, distinguished powertrains are ICEs, PHEVs and BEVs. Hence, six cluster LCAs are used: a regular and large example of each included powertrain. In vehicle LCA studies both material supply chains and in-house production emissions are included. In order to calculate brands' in-house production CO_2 emissions more specifically, not the generic data derived from LCA but the routinely generated scope 1-2 emissions data from EMS is used. Therefore, scope 1-2 emissions are subtracted from production emissions derived from vehicle LCAs. The share of scope 1-2 emissions on overall production phase emission (p) can be calculated and subtracted from total production phase emissions derived from cluster LCAs (LCA_Prod_{veh}) to calculate supply chain emissions per vehicle ($E\_Prod\_SC_{veh}$):

$$E\_Prod\_SC_{veh} = LCA\_Prod_{veh} * (1 - p)$$

(4.5)

$E\_Prod\_SC_{veh}$ for each powertrain and size segment is calculated and set into relation with the resp. vehicle curb weight to derive a CO_2 material supply chain factor (e.g. kg CO_2 per kg vehicle curb weight) for every reference vehicle (sc_w). sc_w is used to extrapolate $E\_Prod\_SC_{veh}$ to $E\_Prod\_SC_{abs}$. For this reason, average vehicle curb weights of the defined segments "regular" (w_r) and "large" (w_l) need to be calculated for each brand. Then, average carbon material supply chain emissions per brand, segments and powertrain are calculated per vehicle:

$$E\_Prod\_SC_{veh,r} = sc_{w,r} * w_r$$

(4.6)

$$E\_Prod\_SC_{veh,l} = sc_{w,l} * w_l$$

(4.7)

The share of "regular" (r) and "large" (l) vehicles per brand on the total number of vehicles sold (n_{veh}) is calculated by summing up the number of regular ($n_{veh,r}$) and large ($n_{veh,l}$) vehicles per brand and dividing them by the total number of vehicles:

$$n_{veh} = n_{veh,r} + n_{veh,l}$$

(4.8)

$$r = \frac{n_{veh,r}}{n_{veh}}$$

(4.9)

$$l = \frac{n_{veh,l}}{n_{veh}}$$

(4.10)

To derive $E\_Prod\_SC_{abs}$, n_{veh} needs to be distinguished between the number of vehicles sold per market ($n_{veh,m,i}$):

$$n_{veh} = \sum_{i=1}^{n} n_{veh,m,i}$$

(4.11)

Subsequently, for each market the shares of the three powertrains ($pt_{m,i}$) are needed to calculate carbon material supply chain emissions per average brand vehicle ($E\_Prod\_SC_{veh}$):

$$E\_Prod\_SC_{veh} = \sum_{i=1}^{3} (E\_Prod\_SC_{veh,r,pt,i} * r + E\_Prod\_SC_{veh,l,pt,i} * l) * pt_{m,i}$$

(4.12)

The average brand vehicle CO_2 material supply chain emissions ($E\_Prod\_SC_{veh}$) are then multiplied with n_{veh} to derive $E\_Prod\_SC_{abs}$:

$$E\_Prod\_SC_{abs} = E\_Prod\_SC_{veh} * n_{veh}$$

(4.13)

4.3 Use phase

Brands' use phase emissions (E_Use_{abs}) are the sum of well-to-tank ($E\_Use_{abs,wtt}$) and tank-to-wheel ($E\_Use_{abs,ttw}$) emissions:

$$E\_Use_{abs} = E\_Use_{abs,wtt} + E\_Use_{abs,ttw}$$

(4.14)

Equally to the calculation of production phase emissions, first, use phase emissions per average brand vehicle (E_Use_{veh}) are calculated:

$$E\_Use_{veh} = \frac{E\_Use_{abs}}{n_{veh}}$$

(4.15)

$$E\_Use_{veh} = E\_Use_{veh,wtt} + E\_Use_{veh,ttw}$$

(4.16)

Tank-To-Wheel

$E\_Use_{veh,ttw}$ describes brands' fleet emissions in g CO_2 per km per average brand vehicle (B_f) multiplied with the vehicle lifetime kilometrage (lk) assumed to be the same for all powertrains:

$$E\_Use_{veh,ttw} = B_f * lk$$

(4.17)

B_f is the product of fleet emissions of average brand vehicles per market ($B_{f,m,i}$) and brand market shares ($b_{m,i}$):

$$B_f = \sum_{i=1}^{n} B_{f,m,i} * b_{m,i}$$

(4.18)

$B_{f,m,i}$ is based on tailpipe emissions of reference ICE ($LCA\_TTW_{ICE,r-l}$) and PHEV ($LCA\_TTW_{PHEV,r-l}$) vehicles of both segments, the number of these types of vehicles per market ($n_{ICE,r-l,m,i}; n_{PHEV,r-l,m,i}$) and $n_{veh,m,i}$, i.e. including BEVs which are calculated with zero TTW emissions:

$$B_{f,m,\mathrm{i}} = \frac{(LCA\_TTW_{ICE,r} * n_{ICE,r,m,\mathrm{i}}) + (LCA_{TTW_{PHEV,r}} * n_{PHEV,r,m,\mathrm{i}}) + (LCA\_TTW_{ICE,l} * n_{ICE,l,m,\mathrm{i}}) + (LCA_{TTW_{PHEV,l}} * n_{PHEV,l,m,\mathrm{i}})}{n_{veh,m,\mathrm{i}}}$$

(4.19)

Group fleet emission averages

In order to compare modelled market-specific Group fleet emissions (OEM_f) with legal requirements, $B_{f,m,i}$ is multiplied with market-specific shares of brands on total Group sold vehicles ($b\_oem_{m,i}$) and eventually summed up:

$$OEM_{f,m} = \sum_{i=1}^{n} B_{f,m,i} * b\_oem_{m,i}$$

(4.20)

Well-To-Tank

$E\_Use_{veh,wtt}$ sums up WTT emissions of vehicles sold in all markets including all powertrains:

$$E\_Use_{veh,wtt} = \sum_{i=1}^{n} E\_Use_{veh,wtt,ICE,m,i} + E\_Use_{veh,wtt,PHEV,m,\mathrm{i}} + E\_Use_{veh,wtt,BEV,m,\mathrm{i}}$$

(4.21)

Both in ICEs' and PHEVs' use phases CO_2 emissions are caused in fossil fuel supply chains. Fossil fuel WTT emissions are calculated based on average WTT emission shares additional to TTW emissions per market ($wtt_{m,i}$) and lk. These shares can e.g. be sourced from LCA databanks taking into account the carbon efficiency of gasoline and Diesel refineries per market. The above described fleet emission average (B_f) includes all powertrains. However, in order to calculate WTT emissions powertrain-specifically, a powertrain-specific fleet emission average is needed. For this reason, both an ICE and PHEV-specific fleet emission average is calculated ($B_{f,ICE}$ and $B_{f,PHEV}$). $B_{f,ICE}$ is calculated by only referring to the number of ICEs in the fleets ($n_{ICE,r-l,m,i}$):

$$B_{f,\mathrm{ICE}} = \sum_{i=1}^{n} \frac{(LCA_{TTW,ICE,r} * n_{ICE,r,m,i}) + (LCA_{TTW,ICE,l} * n_{ICE,l,m,i})}{n_{ICE,m,i}}$$

(4.22)

$B_{f,PHEV}$ is calculated by only referring to the number of PHEVs in the fleets ($n_{PHEV,r-l,m,i}$):

$$B_{f,\mathrm{PHEV}} = \sum_{i=1}^{n} \frac{(LCA_{TTW,PHEV,r} * n_{PHEV,r,m,i}) + (LCA_{TTW,PHEV,l} * n_{PHEV,l,m,i})}{n_{PHEV,m,i}}$$

(4.23)

Average ICE WTT emissions per vehicle ($E\_Use_{veh,wtt,ICE}$) are calculated as follows:

$$E\_Use_{veh,wtt,ICE} = \sum_{i=1}^{n} B_{f,ICE,m,i} * wtt_{m,i} * lk$$

(4.24)

Average PHEV WTT emissions per vehicle ($E\_Use_{veh,wtt,PHEV}$) consist of both fossil fuel induced emissions ($E\_Use_{veh,wtt,PHEV,\mathrm{fuel}}$) and energy consumption induced emissions ($E\_Use_{veh,wtt,PHEV,\mathrm{ec}}$):

$$E\_Use_{veh,wtt,PHEV} = \sum_{i=1}^{n} E\_Use_{veh,wtt,PHEV,fuel,m,i} + E\_Use_{veh,wtt,PHEV,\mathrm{ec},m,\mathrm{i}}$$

(4.25)

$E\_Use_{veh,wtt,PHEV,\mathrm{fuel}}$ is calculated in the same manner as ICE WTT emissions:

$$B\_Use_{veh,wtt,PHEV,fuel} = \sum_{i=1}^{n} B_{f,PHEV,m,i} * wtt_{m,i} * lk$$

(4.26)

$E\_Use_{veh,wtt,PHEV,\mathrm{ec}}$ is based on electricity consumption per average PHEV per market ($EC\_PHEV_{wtt,m,i}$) and market-specific CO_2-intensity of energy mixes ($e_{m,i}$) which can e.g. be obtained from LCA databanks:

$$E\_Use_{veh,wtt,PHEV,ec} = \sum_{i=1}^{n} EC\_PHEV_{m,i} * e_{m,i} * lk$$

(4.27)

$EC\_PHEV_{m,i}$ is calculated by using the electricity consumption of PHEV reference vehicles ($LCA_{WTT,PHEV,ec,r-l}$) and the share of PHEVs in brands' market-specific fleet portfolios ($pt_{PHEV,m,i}$):

$$EC\_PHEV_{m,\mathrm{i}} = \left(LCA_{WTT,PHEV,ec,r} * pt_{PHEV,m,i}\right) + \left(LCA_{WTT,PHEV,ec,l} * pt_{PHEV,m,i}\right)$$

(4.28)

BEV WTT emissions ($E\_Use_{veh,wtt,BEV}$) are calculated in the same manner as $E\_Use_{veh,wtt,PHEV,ec}$:

$$E\_Use_{veh,wtt,BEV} = \sum_{i=1}^{n} EC\_BEV_{m,i} * e_{m,i} * lk$$

(4.29)

$$EC\_BEV_{m,\mathrm{i}} = \left(LCA_{WTT,BEV,r} * pt_{BEV,m,i}\right) + \left(LCA_{WTT,BEV,l} * pt_{BEV,m,i}\right)$$

(4.30)

4.4 End-of-life phase

To calculate EoL absolute emissions (E_EoL_{abs}), EoL emission per vehicle (E_EoL_{veh}) are calculated first:

$$E\_EoL_{veh} = \frac{E\_EoL_{abs}}{n_{veh}}$$

(4.31)

E_EoL_{veh} is calculated based on recycling phase carbon emissions per powertrain derived from LCAs ($LCA\_EoL_{pt,r-l}$), the share of "regular" (r) and "large" (l) vehicles per brand and market-specific powertrain shares ($pt_{m,i}$)

$$E\_EoL_{veh} = \sum_{i=1}^{n} (LCA\_EoL_{pt,r} * pt_{m,i}) + (LCA\_EoL_{pt,r} * pt_{m,i})$$

(4.32)

4.5 Other scope 3 categories

By remodelling emissions of scopes 1-2 and scope 3 categories 1, 11 and 12 over 90% of absolute CO_2 emissions of an OEM are accounted for (Table 4). "Other scope 3 categories" ($E\_Oth_{OEM,abs}$) thus summarises scope 3 categories 2-10 and category 13 ($E\_Oth_{OEM,abs,2-10,13}$). As these scope 3 categories were neither identified as current carbon hotspots nor as main drivers of future emissions, the single categories are not specifically modelled within the CBC method. "Other scope 3 categories" are not directly influenced by choices of powertrains or composition of fleets per brand and market. Therefore, these emission categories are not disaggregated on brand level. "Other scope 3 categories" emissions per vehicle ($E\_Oth_{OEM,veh}$), are finally multiplied by the number of vehicles sold by the OEM ($n_{OEM,veh}$) in the respective year to calculate $E\_Oth_{OEM,abs}$:

$$n_{OEM,veh} = \sum_{i=1}^{n} n_{OEM,veh,i}$$

(4.33)

$$E\_Oth_{OEM,veh} = \sum_{i=2}^{10} E\_Oth_{OEM,veh,i} + E\_Oth_{\mathrm{OEM,veh,13}}$$

(4.34)

$$E\_Oth_{OEM,abs} = E\_Oth_{OEM,veh} * n_{OEM,veh}$$

(4.35)

4.6 Reduction measures

In order to include high-leverage reduction measures identified above ((1) renewable energy sourced for LIB production as well as (2) PHEV and BEV use phase) the presented mode of calculation does not have to be changed. Due to the pursued modular approach of calculating use phase emissions and LIB production separate from cluster vehicle LCAs only the respective input parameters need to be changed. I.e. for these two reduction measures only the assumed market-specific CO_2-intensity of energy mixes ($e_{m,i}$) would have to be modified.

4.7 Future-orientation

Brands' market-specific number of vehicles in the starting year ($n_{veh,\mathrm{y}1,m,\mathrm{i}}$) is correlated with market-specific projections for private mobility demand in a future year, e.g. ten years ahead of the starting year ($d_{y11,m,\mathrm{i}}$). As such, the expected brand fleet size in the modelled future year ($n_{veh,y11,m,i}$) is estimated:

$$n_{veh,y11} = \sum_{i=1}^{n} n_{veh,y1,m,i} * d_{y11,\mathrm{m,i}}$$

(4.36)

After adjusting the future fleet's size, the same mode of calculation for absolute emissions modelling as above is followed. Only the time-specific input parameters change. These include:

- Powertrain mixes per brand and market
- Shares of regular and large vehicles per brand
- Brands' market shares
- In-house production emissions
- Market-specific fossil fuel WTT emission factors
- Market-specific electricity WTT emission factors
- Market-specific demand for mobility services
- Brand and market-specific shares of different mobility services

4.8 Inclusion of mobility services

Based on the modelled size of the brand's fleet (n_{veh}), market-specific load factors for private vehicles ($lf_{pv,m,i}$) and vehicles' lifetime kilometrage (lk), the amount of p-km per market is calculated ($PKM_{m,\mathrm{i}}$):

$$PKM_{m,i} = n_{veh,m,\mathrm{i}} * lf_{pv,m,\mathrm{i}} * lk$$

(4.37)

By summing up $PKM_{m,\mathrm{i}}$ of all brands the amount of p-km on OEM-level is derived (PKM_{OEM}):

$$PKM_{OEM} = \sum_{i=1}^{n} PKM_{m,i}$$

(4.38)

Market-specific shares of mobility service demand on overall mobility demand ($ms_{m,i}$) are used to calculate OEM-level p-km to be served by mobility services in each market ($PKM_{OEM,\mathrm{ms},m,i}$):

$$PKM_{OEM,\mathrm{ms}} = \sum_{i=1}^{n} PKM_{m,i} * ms_{m,\mathrm{i}}$$

(4.39)

Based on market-specific shares of different mobility services of total demand for mobility services, the amount of p-km provided by each mobility service in each market on OEM-level is calculated. Included mobility services are car sharing (cs), ride hailing (rh) and ride pooling (rp):

$$PKM_{OEM,\mathrm{cs}} = \sum_{i=1}^{n} PKM_{OEM,ms,m,i} * cs_{m,\mathrm{i}}$$

(4.40)

$$PKM_{OEM,\mathrm{rh}} = \sum_{i=1}^{n} PKM_{OEM,ms,m,i} * rh_{m,\mathrm{i}}$$

(4.41)

$$PKM_{OEM,\mathrm{rp}} = \sum_{i=1}^{n} PKM_{OEM,ms,m,i} * rp_{m,\mathrm{i}}$$

(4.42)

The needed number of vehicles for each mobility service in each market is calculated in two ways. Needed car sharing vehicles in each market ($n_{cs,veh,m,\mathrm{i}}$) are derived from load factors ($lf_{cs,m,i}$) and lifetime vehicle kilometrage (lk):

$$n_{OEM,veh,\mathrm{cs},m,\mathrm{i}} = \frac{PKM_{OEM,\mathrm{cs},m,\mathrm{i}}}{lf_{cs,m,\mathrm{i}} * lk}$$

(4.43)

Needed ride hailing ($n_{OEM,veh,\mathrm{rh},m,\mathrm{i}}$) and ride pooling vehicles ($n_{OEM,veh,\mathrm{rp},m,\mathrm{i}}$) are derived in the same way as for car sharing except that the lifetime vehicle kilometrage (lk) is corrected for the share of empty travels (et):

$$n_{OEM,veh,\mathrm{rh},m,i} = \frac{PKM_{OEM,\mathrm{rh},m,\mathrm{i}}}{lf_{rh,m,\mathrm{i}} * (lk - (lk * et))}$$

(4.44)

$$n_{OEM,veh,\mathrm{rp},m,i} = \frac{PKM_{OEM,\mathrm{rp},m,\mathrm{i}}}{lf_{rp,m,\mathrm{i}} * (lk - (lk * et))}$$

(4.45)

$n_{OEM,veh,\mathrm{cs},m,i}$, $n_{OEM,veh,\mathrm{rh},m,\mathrm{i}}$ and $n_{OEM,veh,\mathrm{rp},m,i}$ are distributed among ICEs, PHEVs and BEVs according to mobility service specific powertrain shares for each market, e.g. for car sharing ($pt_{cs,ICE,m,i}, pt_{cs,PHEV,m,i}, pt_{cs,BEV,m,i}$):

$$n_{OEM,veh,cs,ICE,m,\mathrm{i}} = n_{OEM,veh,m,i} * pt_{cs,ICE,m,i}$$

(4.46)

$$n_{OEM,veh,cs,PHEV,m,i} = n_{OEM,veh,m,i} * pt_{cs,PHEV,m,i}$$

(4.47)

$$n_{OEM,veh,cs,BEV,m,i} = n_{OEM,veh,m,\mathrm{i}} * pt_{cs,BEV,m,i}$$

(4.48)

After having calculated the number of mobility service vehicles, the remaining number of private vehicles per brand, market and powertrain are derived. Based on the initially calculated total amount of p-km per brand and market ($PKM_{m,i}$) and market-specific shares of mobility service demand on total mobility demand ($ms_{m,\mathrm{i}}$) the remaining amount of p-km provided by private vehicles per brand and market ($PKM_{pv,m,i}$) is calculated:

$$PKM_{pv,m,i} = PKM_{m,i} * (1 - ms_{m,\mathrm{i}})$$

(4.49)

The respective amount of brand and market-specific private vehicles ($n_{veh,pv,\mathrm{m},\mathrm{i}}$) is derived based on $PKM_{pv,\mathrm{m},\mathrm{i}}$, $lf_{pv,m,i}$ and lk:

$$n_{veh,pv,\mathrm{m},\mathrm{i}} = \frac{PKM_{pv,\mathrm{m},\mathrm{i}}}{lf_{pv,m,\mathrm{i}} * lk}$$

(4.50)

The distribution of $n_{veh,pv,\mathrm{m},\mathrm{i}}$ in ICE, PHEV and BEV vehicles is derived according to the mode of calculation shown above for car sharing vehicles.

4.9 Interpolation between modelling points

OEM absolute emissions throughout the whole modelling timespan are calculated two-fold. Depending on data availability, several annual emissions are specifically modelled by applying the modes of calculation described above. Annual emissions in between specifically modelled years are linearly interpolated. In the subsequent method application case study (5) only specific data for the years 2015, 2025, 2030 and 2050 could be obtained. This data structure is exemplarily included in the below equations:

$$y = y_1 + (x - x_1)\frac{y_2 - y_1}{x_2 - x_1}$$

(4.51)

$$E_{\text{OEM},abs,x} = E_{\text{OEM},abs,2015} + (x - 2015)\frac{E_{OEM,abs,2025} - E_{OEM,abs,2015}}{2025 - 2015}$$
$$\text{for } 2015 \leq x \leq 2025$$

(4.52)

$$E_{\text{OEM},abs,x} = E_{\text{OEM},abs,2015} + (x - 2015)\frac{E_{OEM,abs,2030} - E_{OEM,abs,2015}}{2030 - 2015}$$
$$\text{for } 2026 \leq x \leq 2030$$

(4.53)

$$E_{\text{OEM},abs,x} = E_{\text{OEM},abs,2015} + (x - 2015)\frac{E_{OEM,abs,2050} - E_{OEM,abs,2015}}{2050 - 2015}$$
$$\text{for } 2031 \leq x \leq 2050$$

(4.54)

The sum of absolute emissions of the whole modelling timespan is calculated as follows:

$$E_{OEM,abs} = \sum_{i=2015}^{2050} E_{OEM,abs,i}$$

(4.55)

4.10 Carbon budget compliance

Finally, the sum of specifically modelled and interpolated absolute emissions is set into relation with the externally calculated carbon budget. Therefore, the difference ($Cdiff$) between modelled absolute emissions ($E_{OEM,abs}$) and carbon budget (CB) is calculated:

$$\text{Cdiff} = CB - E_{OEM,abs}$$

(4.56)

4.11 The CBC method: graphical overview

A detailed overview of the CBC method's data flows is provided in Figure 27 - Figure 30.

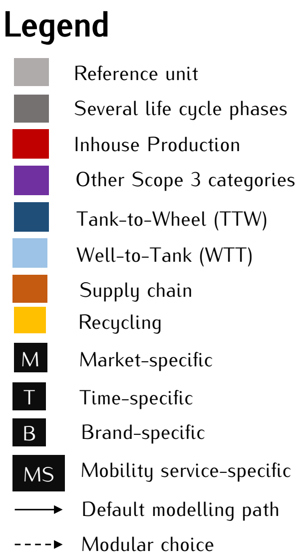


Figure 27 Legend of the CBC Method Parts 1-3 below.

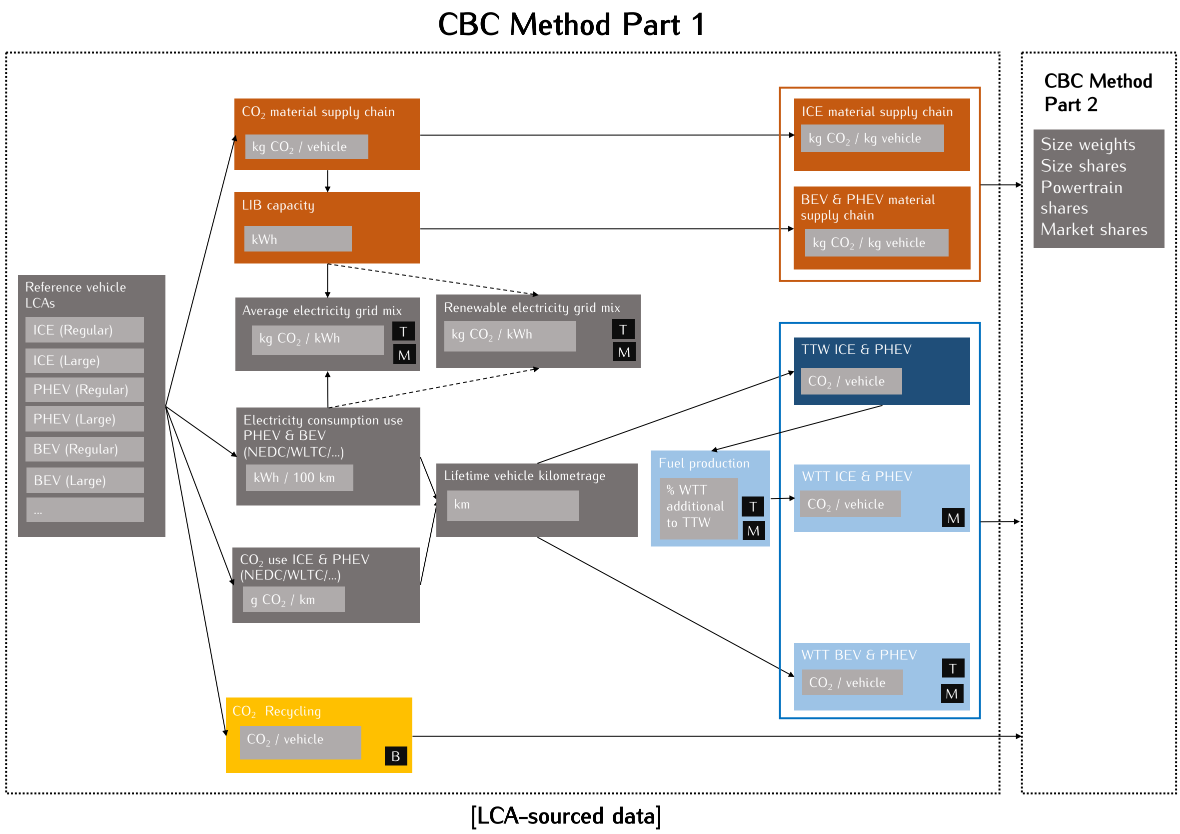


Figure 28 CBC Method Part 1: Data flows and requirements of LCA-sourced data. Part 1 is connected to Part 2 (Figure 29).

CBC Method Part 2

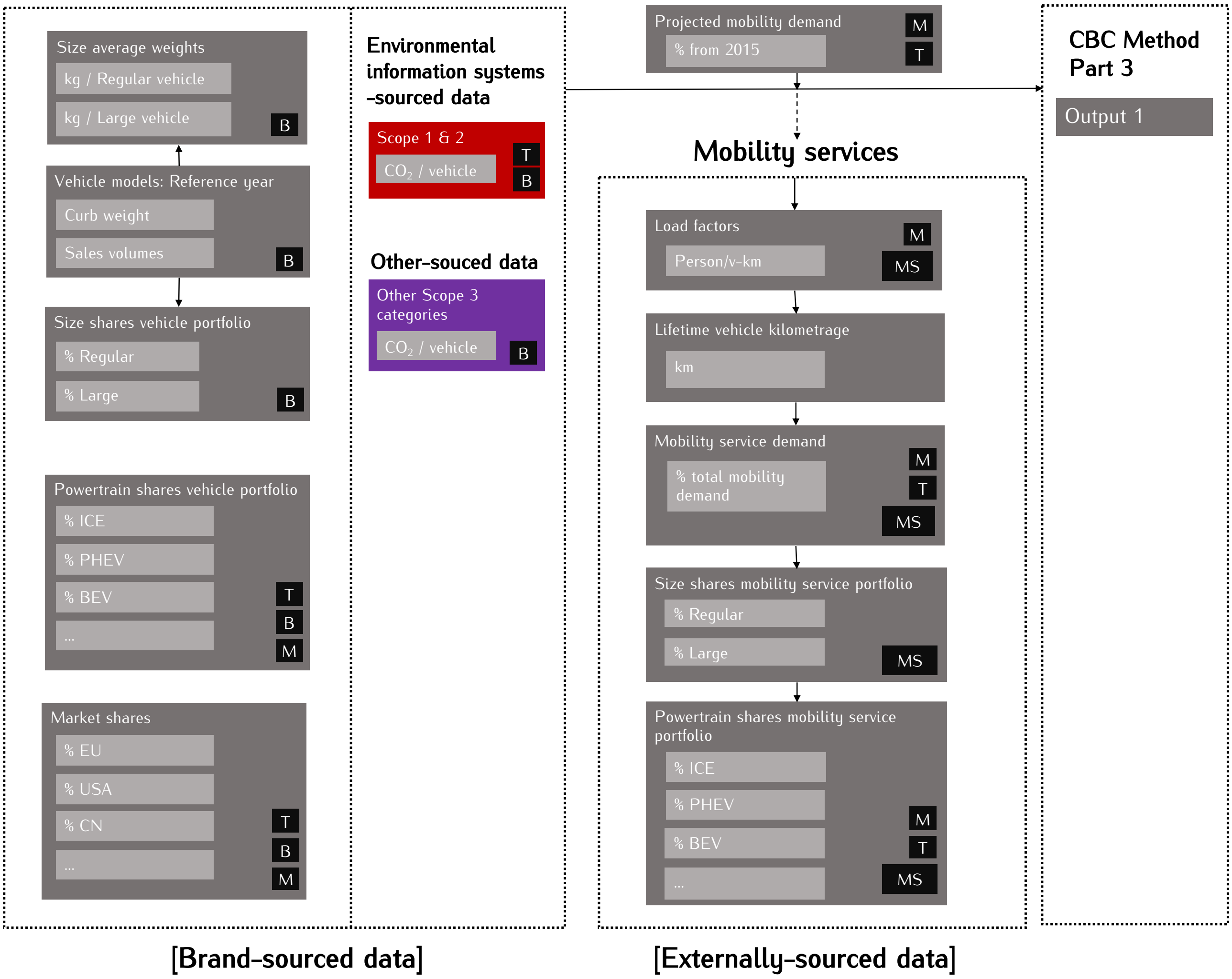


Figure 29 CBC Method Part 2: Data flows and requirements of Brand-sourced data and externally-sourced data. Part 2 is connected to Part 3 (Figure 30).

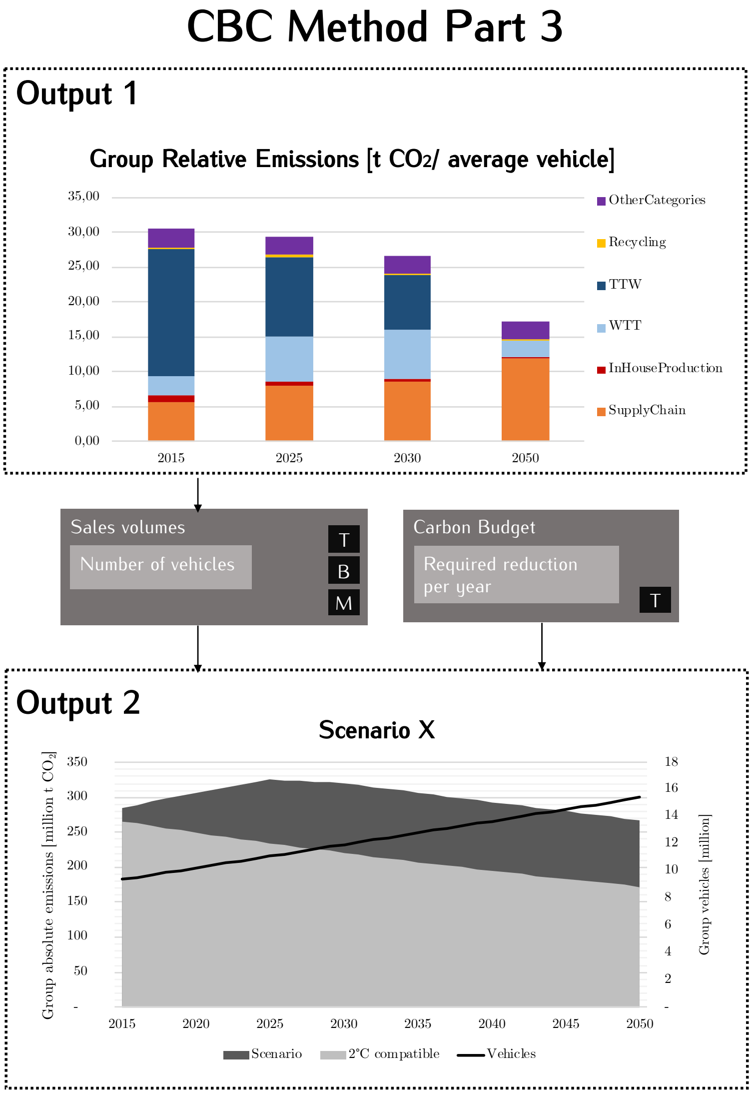


Figure 30 CBC Method Part 3: Output 1 (relative emissions) and output 2 (absolute emissions) in relation to an externally calculated carbon budget.

4.12 Scenario analysis

The CBC method as modelling instrument is meant to be used for scenario analysis in order to evaluate efficient decarbonisation strategies for OEMs. Therefore, the procedure to develop and analyse scenarios is specified below. Scenario analysis has become a common approach to depict possible future developments and impacts of pursued actions within a defined scope by using quantitative modelling techniques (Tourki et al., 2013). However, van Notten (2005) highlights that scenarios are unable to predict the future. His definition of scenarios is used in the following:

“Scenarios are consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present and future developments, which can serve as a basis for action.” (van Notten, 2005, p. 20)

Applied to the CBC method, the above definition clarifies that the modelling results are not showing *the* future carbon emissions pathway of the analysed OEM. The scenario results are rather depicting how probable developments of the OEM’s main emission drivers influence the company’s CO_2 emissions.

Schebek et al. (2016) use a scenario analysis approach proposed by Kosow and Gaßner (2008) which distinguishes between two main phases of the scenario analysis: (a) developing scenarios, (b) analysing scenarios with a modelling instrument. The two main phases entail different work packages. First, goal and scope of the planned scenarios need to be described. Here, the CBC method can draw on the goal and scope requirements defined within the O-LCA handbook (Martínez Blanco et al., 2015). These are i.a. the company to be studied, the system boundary, data requirements and sources, included products and services of the assessed company as well as assumptions and limitations. Second, key parameters influencing the modelling results have to be identified and their projected development within the modelling timespan analysed. Based on this analysis, the single scenarios are described in detail. Finally, the scenarios are analysed within the modelling instrument. As a further development of Kosow and Gaßner's (2008) approach, the scenario analysis step within the CBC method should entail (a) a model calibration with past emissions data, (b) a description of results, (c) a sensitivity analysis and (d) a discussion of the results to evaluate the most efficient decarbonisation options for the analysed OEM.

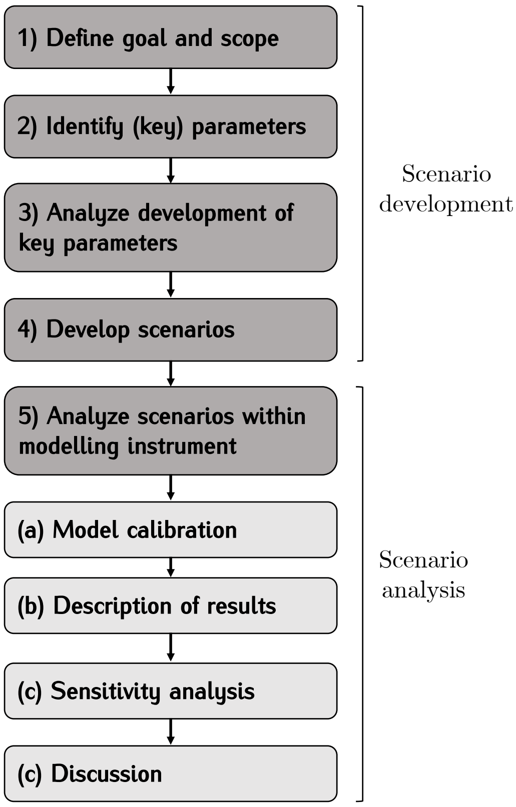


Figure 31 Working phases of scenario development and analysis based on Kosow and Gaßner (2008) (illustration modified by the author).

As the LCA methodology is the main structuring element for the CBC method, the recommendations for sensitivity analysis by the European Commission as provided in their International Life Cycle Data System (ILCD) handbook (EC-JRC, 2010) can be used. The authors recommend to focus on testing input parameters which both lack quality and have a high impact on the scenarios' results to determine the overall sensitivity (Figure 32).

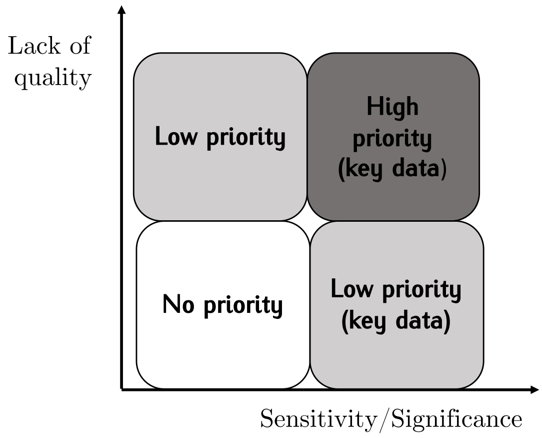


Figure 32 Sensitivity analysis with focus on data with high significance and low quality (based on EU-JR (2010)).

5 Method application: case study Volkswagen Group

The CBC method's mode of calculation described above is applied in an exemplary case study at VW Group to test its ability to model possible future carbon emissions of the company. Based on the scenario development procedure depicted in Figure 31, the scenarios analysed in this case study are developed and described in 5.1. An overview of scenarios is provided in Table 52. Subsequently, the CBC method is tested for its ability to re-model past reported emissions data to adjust the carbon budget accordingly (5.2). In 5.3 the modelling results are presented. Finally, an analysis of sensitivity (5.4) is performed followed by a summarising chapter (5.5) and the discussion of modelling results in chapter 6.5 which is embedded in the overall discussion chapter of this dissertation.

5.1 Scenario development

The modelling results are supposed to support managers of automotive OEMs in their decision-making process. The CBC method aims at facilitating the choice of the most efficient measures to reduce absolute CO_2 emissions, that is, to focus on the most promising leverages to stay within a Paris Agreement-compatible carbon budget until 2050. In this exemplary application of the CBC method, public data as of mid-2019 is used exclusively. OEMs' CO_2 experts modelling carbon emissions within the CBC method themselves will have access to internal data with higher quality and resolution than the data used in this case study. Furthermore, the research fields of i.a. mobility services and battery production can be expected to evolve rapidly thus generating new potential input data. The focus of this chapter thus solely lies on demonstrating how the CBC method works and how it can be applied.

5.1.1 Goal and scope definition

The goal of the following scenario analysis is to find out whether and how VW Group can stay within a 2 °C-compatible carbon budget. Both goal and scope are embedded in the preliminary method development and derivation (Chapters 1-4). The CBC method, being the modelling instrument for the following analysis, was developed based on requirements which are, in turn, based on the external framework this dissertation is set it. Table 25 provides a summary of the analyses' scope and the respective influencing factors.

Goal and scope are dependent on the provisions of the Paris Agreement. As only publicly available data is used in this exemplary case study, the company-specific SDA tool to derive Paris Agreement-compatible reduction targets cannot be used. Therefore, the absolute-based approach SBTi calculated to support a global 2 °C target is used. SBTi (2018b) calculated the global absolute emissions reduction pathway of at least 49% between 2010 and 2050 (i.e. at least 1.23% reduction per year). This approach is based on the IPCC's Fifth Assessment Report on which the Paris Agreement is built on (SBTi, 2018b). In this analysis, the applied timespan is 2015 to 2050. The base year 2015 is chosen due to the publicly available data provided in the 2015 VW sustainability report and annual report. Choosing a base year in the past is necessary to base future emission pathways modelling on and to calibrate the model. The final year 2050 is set due to it being the target year of both Paris Agreement and SBTi emission reduction calculations. Due to data-availability constraints, not every single year between 2015 and 2050 is modelled but only the base year 2015, the years 2025 and 2030 as well as the target year 2050. In between these modelling points, emissions are linearly interpolated. This approach is in line with the long-term road transport emissions models described in chapter 3.4.4. 2025 was chosen as a modelling point because VW set out their TOGETHER 2025 strategy which entails CO_2 reduction targets that can be incorporated in the scenarios. 2030 was chosen as a modelling point due to data being available for this year in LCA databases and in reports projecting demand for different types of individual motorised mobility.

The scope of annual emissions covered (scope 1-3) is dependent on the requirements set out by the GHG Protocol and thus reported emissions to CDP on which basis the compliance with a SBT-reduction pathway is monitored. VW Group serves as the model company in the following scenario analyses. It was chosen due to its diverse brands, global market coverage and publicly available data used as input for the model.

The geographic scope covered are the current three main markets served by VW: EU, US and China (CN). Again, this scope is chosen due to data availability. Especially, the availability of past, current and future fleet emission legislations. Also, in the company's annual reports explicit information on vehicle sales is provided for these three markets with the EU being grouped together with other markets such as India which serves as a basis for modelling base year emissions (VW, 2016b). Brands included in the scenarios are the LDV-selling brands Volkswagen PKW (VWP), AUDI, ŠKODA, SEAT, Porsche (PAG) and Volkswagen Commercial Vehicles (VWN). Combined, these brands offered 60 LDV models in the base year 2015 which are included in the analysis. Trucks and buses sold by MAN and SCANIA are not included. The brand MOIA is exemplarily included in the scenarios dealing with mobility services as it represents the mobility service segment of the company.

Included powertrains are ICEs, PHEVs and BEVs. CNG- and FCEV-powered vehicles are not included. CNG vehicles are neither currently representing nor in the future expected to represent high shares within VW's fleet (Handelsblatt, 2019). Furthermore, no FCEV LCA study exists of a vehicle that is currently on the market and thus cannot be used as data source for the scenarios. Chosen mobility services to be included are car sharing, ride hailing and ride pooling as OEMs are currently engaging in offering those (see 2.3.1 and Neef et al. (2019)).

Finally, the goal of the CBC method is to provide OEM managers with decision-support for most effective carbon reduction measures. Therefore, the reduction measures expected to provide the highest leverage in reducing carbon emissions were selected for this analysis (see 2.3). Table 25 shows an overview of the scenario analysis' scope.

Table 25 Summary of scenario analysis' scope with respective influencing factors.

Scope		**Influencing factors & justification**
Time	2015-2050	Paris Agreement, IPCC Reports
Geographic	EU, USA, CN	Data availability, VW: 95% market coverage
Emissions	Scope 1-3	GHG Protocol, SBTi
Carbon Budget	-49% (2010-2050)	SBTi (absolute-based approach)
Modelling intervals	2015, 2025, 2030, 2050	Data availability
Company	VW Group	Data availability, diverse brands
Brands	VW PKW, AUDI, ŠKODA, SEAT, PORSCHE, VWN, MOIA	Major LDV-selling brands resp. mobility service brand
Models	60	Complete product portfolio 2015
Powertrains	ICE, PHEV, BEV	Data availability
Mobility services	Car sharing, ride hailing, ride pooling	Services that OEMs are currently engaging in.
Reduction measures	Renewable energy in LIB production and PHEV, BEV use phase.	Highest CO_2 reduction potential at the vehicle level and data availability.

Possible future emission pathways of the company are modelled based on current projections of key parameters which serve as default settings for the scenarios. In the following, first, an overview of the scenario field is provided, second, default settings for all scenarios are described and, third, storylines and data inputs of the single scenarios are defined.

5.1.2 Scenario field

Nine scenarios are modelled in total (Figure 33). Scenario 1 acts as both the baseline and Business-as-usual (BAU) scenario. Scenarios 2 and 3 (S2, S3) are modifications of scenario 1 (S1) applying modified input parameters and/or modelling additional sub-groups of the company's business portfolio. The scenario 2 sub-group (blue) comprises three scenarios. In scenario 2, the combined impact of the two reduction measures "Green LIB production" and "Green electrified use phase" on the Groups absolute emissions is modelled. Scenarios 2a and 2b each analyse the single impact of each of the measures. The scenario 3 sub-group (fawn) comprises four scenarios focusing on mobility services' impact on the Group's absolute carbon emissions. In scenario 3 the impact of a combination of different mobility services is analysed. Scenarios 3a-c (S3a-c) target each one of the included mobility services: (a) car sharing, (b) ride hailing, (c) ride pooling. As such, possible differences in impacts on absolute emissions between the services are evaluated to provide more specific decision-making support for managers. Scenario 4 combines scenarios 2-3 evaluating the combined impact on VW's emissions of both vehicle-level reduction measures and alteration of the fleet composition by mobility services. All scenarios are modelled by applying the CBC method. Storylines of the single scenarios are provided below.

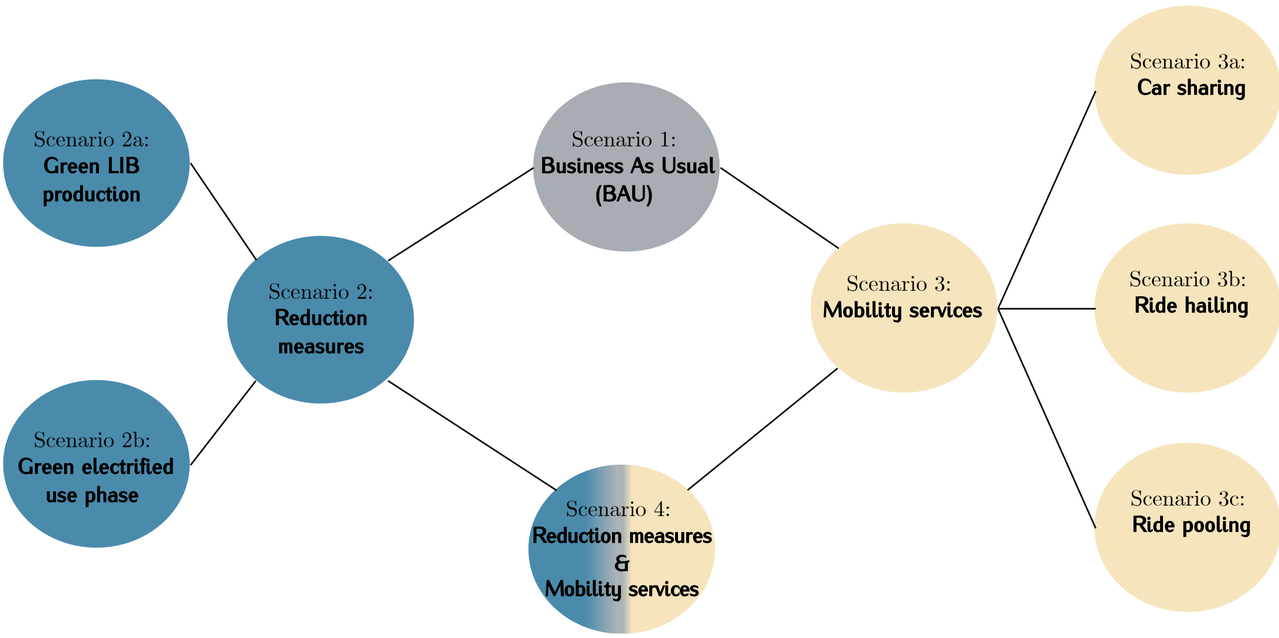


Figure 33 Overview of the scenarios modelled in the case study. Scenarios 2 & 3 are modifications of scenario 1. Scenarios 2 a-b are variations of scenario 2. Scenarios 3 a-c are variations of scenario 3. Scenario 4 represents a combination of scenarios 2 and 3.

5.1.3 Classification of scenarios

In line with OECD recommendations, van Notten's (2005) categorization is used in the following to classify the scenarios that are to be analysed (OECD, 2019). Three macro characteristics concerning (a) goals, (b) design and (c) content of scenarios with respective sub-characteristics are used for classification. Table 26 provides an overview of classification results.

The goal of all scenarios analysed in this dissertation is *decision-support*. The comparison of the different scenarios is meant to give indications for concrete strategic options that should be pursued to stay within the company's carbon budget. According to van Notten (2005), all scenarios are *normative* as both probable future emission pathways (S1 and S3a-c) and strategic measures are being modelled (S2a-b and S4). The vantage point from which all scenarios are developed is in the past (2015). From this point, both the following years' past emissions as well as future years' emissions are being modelled. Thus, both *backcasting* and *forecasting* is applied in the scenarios. The subject of these analyses are *contextual* *institution-based* scenarios as parameters outside the direct scope of VW Group's influence sphere are included (e.g. energy mixes). The time-scale is *long-term* as a span over 25 years is being computed. The spatial scale is both *national* (USA, CN) and *supra-national* (EU).

The scenario process design follows a *formal* approach because the scenarios are developed based on quantifiable knowledge, i.e. projections are key emission parameters' developments. Hence, only quantitative inputs such as data derived from other quantitative models (e.g. ITF's model for mobility demand) is used in the process. The method of data collection is described as *desk research* as input parameters are collected through literature research.

The scenario content is classified as *simple*. Here, "*simple*" refers to the number of chosen parameters and their interconnection. The single input parameters are modelled according to projected trends without influencing each other's development throughout the modelling timespan. The level of integration is therefore classified as *low*. The final state of VW Group's accumulated emissions in 2050 is dependent on the emissions' development between 2015 and 2050. Therefore, the temporal nature of the scenarios is *developmental*: the single modelling steps lead to the end result in a traceable manner. The nature of integrated variables is *heterogeneous* as data inputs describing different factors such as mobility demand based on macro-economic parameters and population growth and the CO_2-intensity of electricity mixes depicting regions' carbon reduction schemes are included. The nature of dynamics addressed in the scenarios is identified as both *trend* and *peripheral*. In S1 and S2a-b input parameters are based on extrapolation of trends (e.g. demand for passenger vehicles), in S3a-c and S4 a discontinuous pathway is computed as mobility services are included as a disruptive element.

Table 26 Macro and micro characteristics of analysed scenarios according to van Notten (2005).

Macro characteristics	Micro characteristics
Goal: decision support	Norms: normative
	Vantage point: back-casting & forecasting
	Subject: contextual institution-based
	Time scale: long-term
	Spatial scale: national & supra-national
Process: formal	Inputs: quantitative
	Data collection: desk research
Content: simple	Level of integration: low
	Temporal nature: developmental
	Nature of variables: heterogeneous
	Nature of dynamics: trend (S1 and S2a-b) & peripheral (S3a-c and S4)

5.1.4 Default settings: Data inputs and assumptions

The default settings are assumptions and data inputs applicable to all scenarios if not explicitly stated otherwise. The chosen default settings resemble the above analysed development of OEMs' key emission drivers (2.3) used to develop the CBC method. In the following, default assumptions (1-12) with respective specific data inputs valid for the entire modelling timespan (2015-2050) are presented.

(1) VW Group's global market share of total LDV sales is constant.
(2) VW Group brands' share on Group total LDV sales and market representation are constant.

Based on total LDV sales in the starting year 2015, the Group's vehicle sales are developing according to market-specific prognoses. Possible losses or gains in VW Group's 2015 market share during the modelling timespan are not considered. As described above, based on available data from the past (2015) and time- and market-specific prognoses, future years' emission are modelled. The Group's 2015 fleet size and composition is sourced from the 2015 annual report (VW, 2016b). The given information is, however, not matching the needed format for the model's data inputs. Therefore, the information given in the annual report is processed as described below.

The total figure of globally sold LDVs in 2015 is 9,374,000. This number includes sales by VWP, AUDI, ŠKODA, SEAT, PAG, VWN and BENTLEY in the markets EU & Other, North America, South America and Asia-Pacific. As BENTLEY sold eleven cars only, it is not specifically modelled but its sales are equally distributed to the six major brands. The brands active in China, sell vehicles via the Group's Joint Ventures (JV) summarised as "VW China" in the annual report. Therefore, VW China's 3,456,000 vehicles are redistributed to the brands active in China based on their market and Group fleet shares. Without VW China the brands hold the following shares within the Group fleet (Table 27).

Table 27 2015 LDV sales per brand without VW China (VW, 2016a).

Brand	Brand sales 2015 w/o VW China [Volumes]	Share [%]
VWP	4,424,000	55
AUDI	1,529,000	19
ŠKODA	800,000	10
SEAT	544,000	7
PAG	219,000	3
VWN	456,000	6
Sum	7,972,000	100

Based on the brands' Group fleet shares indicated in Table 27, the 9,374,000 globally sold LDVs are redistributed to the brands (Table 28).

Table 28 Brand sales with added sales of VW China according to shares in Table 27.

Brand	Brand sales redistributed [Volumes]	Share [%]
VWP	5,202,029	55
AUDI	1,797,898	19
ŠKODA	940,692	10
SEAT	639,671	7
PAG	257,515	3
VWN	536,195	6
Sum	9,374,000	100

Brands' market coverages are indicated for the four markets mentioned above. As neither current nor future legislative standards for CO_2 fleet emission standards exist for South America as a combined market, the South American market shares (5% on Group level) are redistributed equally to the other markets the respective brand is active in. Depending on the brand, South American market shares are redistributed to either the two or three markets the brand is covering. The resulting market shares are depicted in Table 29.

Table 29 Market shares per brand. South American market shares were redistributed to the respective markets each brand is covering.

Brand	EU share [%]	USA share [%]	CN share [%]	Sum [%]
VWP	35.8	12.8	51.3	100
AUDI	48.0	14.0	38.0	100
ŠKODA	71.0	-	29.1	100
SEAT	93.9	6.1	-	100
PAG	37.8	26.8	35.4	100
VWN	87.7	4.5	7.9	100
Sum	100	100	100	

(3) VW Group's vehicle sales are developing according to market prognoses.

No publicly available data on VW Group's expected market-specific growth is available. Therefore, it is assumed that vehicles sales will develop according to market prognoses. As shown in 2.3.1, different projections on mobility demand in the markets EU, USA and CN exist. As default input parameters data from the ITF Transport Outlook 2017 is chosen (OECD/ITF, 2017). The authors provide an Excel sheet indicating projected urban private mobility demand which is synonymous with demand for private vehicles for OECD and non-OECD countries. The markets EU and US are assigned to the OECD growth rates, the market China to the non-OECD growth rates. The report's modelling points resemble the time steps chosen in this scenario analysis: data is provided for 2015, 2030, 2050. For modelling point 2025 the years 2030 and 2015 are interpolated (see Table 30).

Table 30 Change in urban private mobility demand based on OECD/ITF (2017). Change 2015-2025 is linearly interpolated (*). EU and USA are assigned OECD rates, CN is assigned non-OECD growth rates.

Region	Year	Urban private mobility demand [billion p-km]	Change in demand [%] 2015 - year
OECD (EU, US in scenario analysis)	2015	8,953	-
	2025	9,579*	+7*
	2030	9,901	+11
	2050	11,934	+33
Non-OECD (CN in scenario analysis)	2015	7,467	-
	2025	10,827*	+45*
	2030	12,462	+67
	2050	19,174	+157

(4) VW Group brands' fleets have the same time and market-specific powertrain shares.

Publicly available information on powertrain portfolios of single VW brands or markets is rare. Nonetheless, the VW Group published their planned market-specific powertrain portfolio for 2040 (Handelsblatt, 2019). The powertrain shares are depicted in Table 31. In the IEA reference technology scenario (RTS), for the 2060 both shares of ICE and PHEV are estimated to be around 33%, BEV and FCEVs around 31% and CNG-powered vehicles around 3% (IEA, 2017a). The VW Group 2040 powertrain shares thus surpass the global projection of powertrain shares the IEA forecasts for 2060. In the 2015 annual report no powertrain fleet composition is indicated. Therefore, PHEV and BEV shares in all markets are assumed to be zero percent (Table 32).

Table 31 VW Group's planned powertrain portfolio in 2040 according to Handelsblatt (2019).

Volkswagen powertrain shares in 2040 [%]				
Powertrain / Market	ICE	PHEV	BEV	FCEV
EU	0	10-20	70	10-20
US	5	10-25	60	10-25
CN	5	0	85	10-25

However, as indicated above, only ICE, PHEV and BEV are included in the scenarios. Therefore, the FCEV shares are grouped together with the BEV shares in accordance with the approach by IEA (2017a). Based on these modified powertrain shares for 2040 powertrain portfolio compositions of the modelling years 2025 and 2030 are interpolated. As the 2040 powertrain shares show a significant reliance on electrified vehicles, it is assumed that by 2050 all sold vehicles will be fully electrified. The resulting default settings of powertrain shares for all LDV brands included in the scenario are depicted in Table 32. Though it would be more coherent to linearly interpolate between the assumption of a 100% BEV fleet in all markets in 2050 and 2015 shares, this approach is chosen as the increase of PHEV shares until 2040 can be included in this manner.

Table 32 Modelled powertrain shares used for all LDV-selling brands for modelling points 2015, 2025, 2030 and 2050.

Modelled powertrain shares applicable for all LDV brands [%]					
Powertrain / Market	ICE	PHEV	BEV	Year	Source
EU	100	0	0	2015	Assumption
US	100	0	0		
CN	100	0	0		
EU	59.65	6.25	34.11	2025	Interpolation based on 2040 shares
US	61.65	7.25	31.11		
CN	61.65	0.25	38.11		
EU	39.76	9.16	51.07	2030	Interpolation based on 2040 shares
US	42.76	10.66	46.57		
CN	42.76	0.16	57.07		
EU	0	0	100	2050	Assumption
US	0	0	100		
CN	0	0	100		

These market- and time-specific powertrain shares are connected to the reference vehicles cluster-LCA studies. In connection with brands' fleet composition of regular and large vehicles (see assumption 6), WTW emissions, supply chain emissions and recycling emissions are calculated. As for TTW emissions, past, current and future fleet averages legally required in the EU, US and CN are used as reference to cross-check whether the model estimates fleet averages in line with the respective legislation. Fleet averages under the New European Driving Cycle (NEDC) are used throughout the model. In the EU, emission averages are reported under this test regime until 2020 before reporting under Worldwide Harmonised Light-Duty Vehicles Test Cycles (WLTC) is required (Culver, 2018). Likewise, reference vehicles' TTW emissions could only be obtained in NEDC. Available information on legally required emission averages are depicted in Table 33.

Table 33 Assumed legally required fleet averages as at November 2019. For 2050 and partly for 2030 no planned legislations could be found.

Required fleet average [g CO_2/km]					
Market (test cycle)	**2015**	**2025**	**2030**	**2050**	**Source & comment**
EU (NEDC)	130	80.8	59.4	-	2015: (ICCT, 2018a), 2025 & 2030:(European Parliament, 2018a)
US (NEDC)	153.8	96.9	-	-	(ICCT, 2017)
CN (NEDC)	161.0	116.7	-	-	(ICCT, 2017) 2025 fleet emission average is assumed from published 2020 target.

The reference vehicles with respective TTW emissions according to NEDC are depicted in Table 34.

Table 34 Reference vehicle with respective TTW emission averages per km. In case a range of emissions was indicated, the highest figure is used. All emission averages are NEDC values.

Vehicle	**Reference model**	**TTW emissions according to NEDC [g CO_2/km]**	**Source**
Regular ICE	Golf TSI	110	(VW, 2019a)
Large ICE	Audi Q7 3.0 TDI	181	(AUDI, 2019a)
Regular PHEV	Golf GTE Hybrid	39	(VW, 2019b)
Large PHEV	Audi Q7 e-tron quattro	50	(AUDI, 2017)
Regular BEV	e-Golf	0	BEVs do not cause TTW CO_2 emissions.
Large BEV	Audi e-tron	0	

(5) Vehicles' lifetime kilometrage is constantly 150,000 km.

According to the lifetime mileage of OEMs used in their past emissions reporting (see 2.2.1), it is assumed that all vehicles (private and mobility services) are used for a total of 150,000 km. This lifetime kilometrage is assumed to be constant in the covered markets and timespan.

(6) VW Group brands' average vehicle weights are constant over time.

Brands' average vehicle curb weights are needed to calculate material supply chain emissions of ICE vehicles. In the 2015 annual report brands' models with respective sales volumes are provided. For each model, the highest indicated curb weight provided in the models' technical data sheets is selected. Regular-sized vehicles were defined as weighing up to 1,700 kg, large-sized vehicles as weighing more than 1,700 kg. For example, VW Passat's curb weight is roughly 1,600 kg and is thus classified as "regular" (VW, 2016c). Each model is classified as either "regular" or "large". In the following, for each brand average sales-weighted curb weights of "regular" and "large" vehicles are calculated (see Appendix Table 61-Table 66). An overview of brands' "regular" and "large" shares with respective curb weights is provided in Table 35.

Table 35 Brands' shares of regular and large vehicles with respective average curb weights. The underlying model-specific curb weights are listed in the Appendix Table 61-Table 66.

Brand	Share regular [%]	Share large [%]	Average curb weight regular [kg]	Average curb weight large [kg]
VWP	97	3	1,303	2,036
AUDI	40	60	1,354	1,882
ŠKODA	100	-	1,275	-
SEAT	93	7	1,161	1,805
PAG	23	77	1,445	2,017
VWN	37	63	1,576	2,060

PHEV and BEV vehicle curb weights cannot be calculated in the same manner as most of the brands' currently do not have both PHEV and BEV models in their fleets. Material supply chain emissions of electrified vehicles are therefore calculated based on curb weights of the reference PHEV and BEV vehicles (Table 36) and brand-specific "regular" and "large" shares (Table 35).

Table 36 Electrified reference vehicles with respective curb weights.

Vehicle	Reference model	Curb weight [kg]	Source
Regular PHEV	Golf GTE	1599	(VW, 2019b)
Large PHEV	Audi Q7 e-tron quattro	2520	(AUDI, 2017)
Regular BEV	e-Golf	1615	(VW, 2019c)
Large BEV	Audi e-tron advanced 55 quattro	2565	(AUDI, 2019b)

Because vehicle curb weights and brands' shares of "regular" and "large" vehicles are assumed to remain constant, recycling emissions per vehicle remain also constant. In Handelsblatt (2019), VW published an LCA-based powertrain comparison of Golf TSI (ICE), Golf GTE (PHEV) and e-Golf (BEV). In the article, values are given in g CO_2 per kilometre over life cycle and a lifetime kilometrage of 200,000 km is assumed. Therefore, the emission information (Table 37) is converted to t CO_2/vehicle. For the AUDI reference vehicles no specific recycling emissions could be found. Therefore, recycling emissions are extrapolated from the VW reference vehicles based on the differences in curb weights between the powertrain-specific reference vehicles under the assumption that recycling emissions are linearly correlated with curb weight.

Table 37 Recycling CO_2 emissions of reference vehicles. Emissions for AUDI vehicles are extrapolated based on the differences in powertrain-specific curb weights.

Vehicle	Reference model	Recycling [t CO_2/vehicle]	Source
Regular ICE	Golf TSI	0.2	(Handelsblatt, 2019)
Large ICE	Audi Q7 3.0 TDI	0.3	Extrapolated from Golf TSI based on curb weight
Regular PHEV	Golf GTE	0.2	(Handelsblatt, 2019)
Large PHEV	Audi Q7 e-tron quattro	0.3	Extrapolated from Golf GTE based on curb weight
Regular BEV	e-Golf	0.2	(Handelsblatt, 2019)
Large BEV	Audi e-tron advanced 55 quattro	0.3	Extrapolated from e-Golf based on curb weight

(7) CO_2-intensity per kg vehicle material is constant for all powertrains.
(8) LIB technologies and capacities are constant based on reference vehicles.

It is assumed that material compositions and respective CO_2-intensities remain constant for all powertrains. For ICE reference vehicles, production supply chain emissions provided in LCA studies are adjusted for scope 1-2 emissions. According to VW (2017b), 2015 Scope 1-2 and Scope 3 category 1 emissions add up to 65 million t CO_2. Scope 1-2 make up 14% of these emissions. Therefore, LCA-sourced production emissions are lowered by 14% to avoid double counting (see Table 38). Scope 1-2 emissions are considered more specifically in the model by using EMS-based data (see assumption 12).

Table 38 ICE reference vehicles' assumed constant material supply chain emissions.

Vehicle	Reference model	CO_2 production [t CO_2/ vehicle]	Source	Share scope 1-2 on scope 3 cat. 1 [%]	CO_2 material supply chain [t CO_2/vehicle]	Emission factor [kg CO_2/kg vehicle]
Regular ICE	Golf TSI	5.2	(Handelsblatt, 2019)	14 (VW, 2017b)	4.5	3.6
Large ICE	Audi Q7 3.0 TDI	12	(AUDI, 2016a)		10.3	4.8

LCA-based production emissions for electrified vehicles are adjusted for scope 1-2 emissions as described above for ICE reference vehicles. Additionally, they are adjusted for LIB production emissions (see Table 39). These were identified as one of the main emission drivers for OEMs (see 2.3). LIB production emissions are thus calculated separately from other material supply chain emissions. As such, a modular approach allows for changing CO_2-intensities of LIB production in scenario analysis. Reference vehicles' LIB capacities were correlated with the energy intensity factor provided by Romare and Dahllöf (2017) to calculate LIB production emissions. The default emission factor of 138 kWh electricity/kWh LIB represents the mean of indicated upper and lower electricity requirements. It is likely that VW will build LIBs within the EU (Eckl-Dorna, 2019). Therefore, LIB production is connected to time-specific CO_2-intensities of the applied EU electricity mix (see Table 42).

For a large BEV like the reference vehicle "AUDI e-tron advanced 55 quattro" no specific LCA study has been published yet. Therefore, CO_2 emissions caused during production had to be estimated. Large PHEV reference vehicle AUDI Q7 e-tron quattro and AUDI e-tron advanced 55 quattro have similar curb weights (roughly 2.5 t). When applying the energy intensity factor of Romare and Dahllöf (2017) to Q7's LIB capacity, the 17.3 kWh LIB production alone causes 1.1 t CO_2 with the 2016 European energy grid mix. When subtracting these 1.1 t CO_2 from the overall production emissions of 16.2 and adding the CO_2 intensity of the 95 kWh LIB, the large BEV is allocated 21.1 t CO_2/vehicle for production phase emissions. At this point, I want to stress again that these figures are assumption only.

Table 39 Electrified reference vehicles' material supply chain and LIB production emissions.

Model	CO_2 prod. incl. LIB [t CO_2/ vehicle]	Source	Share scope 1-2 on scope 3 cat. 1 [%]	CO_2 material supply chain incl. LIB [t CO_2/vehicle]	LIB capacity [kWh]	Source	CO_2 material supply chain excl. LIB [t CO_2/vehicle]	Emission factor [kWh electricity / kWh LIB]
Golf GTE	8.6	(Handelsblatt, 2019)	14 (VW, 2017b)	7.4	8.7	(VW, 2019b)	6.8	138 (mean value) (Romare and Dahllöf, 2017)
Audi Q7 e-tron quattro	16.2	(AUDI, 2016a)		13.9	17.3	(AUDI, 2017)	12.8	
e-Golf	11.4	(Handelsblatt, 2019)		9.8	35.8	(VW, 2019c)	7.5	
Audi e-tron advanced 55 quattro	21.1	Extrapolated based on (Romare and Dahllöf, 2017)		18.1	95	(ADAC, 2019)	12.1	

Electricity consumption per 100 km of electrified reference vehicles are shown in Table 40.

Table 40 Electricity consumptions of electrified reference vehicles.

Vehicle	Reference model	Electricity consumption [kWh/100km]	Source
Regular PHEV	Golf GTE	12.4	(VW, 2019b)
Large PHEV	Audi Q7 e-tron quattro	19	(AUDI, 2017)
Regular BEV	e-Golf	14.1	(VW, 2019c)
Large BEV	Audi e-tron advanced 55 quattro	24.6	(AUDI, 2019b)

(9) CO_2-intensity of Diesel and Gasoline production is constant and shares of Diesel and Gasoline-powered vehicles among ICE vehicles are constant.

The GaBi software version ts 8.7 (thinkstep) with service pack 36 and 2018 databank is used to calculate CO_2 intensities of market-specific fuel production (thinkstep, 2018). According to ACEA (2019), 45% of sold LDVs in the EU were Diesel-powered and 55% were gasoline-powered in 2018. According to the US Bureau of Transportation Statistics (BTS) (2017), in 2014 ca. 1% of LDVs in the USA were Diesel-powered and 99% were gasoline-powered. ICCT (2018b) states that in 2014, 0% of LDVs produced by Joint Ventures for the Chinese market were Diesel-powered. It is therefore assumed that in the USA and China 100% of LDVs are gasoline powered. The resulting WTT shares [%] additional to TTW emissions [g CO_2/km] are depicted below.

Table 41 Market-specific shares of Diesel- and gasoline-powered LDVs (EU (2018), US & CN (2014)) with resulting WTT emission factors applied for the whole modelling timespan.

Market	Share of Diesel-, gasoline-powered LDVs	Source	Share WTT [%] additional to TTW	Source
EU	45% Diesel, 55% gasoline	(ACEA, 2019)	14	(thinkstep, 2018)
USA	100% Gasoline (rounded)	(BTS, 2017)	16	(thinkstep, 2018)
CN	100% Gasoline	(ICCT, 2018b)	14	(thinkstep, 2018)

(10) CO_2-intensities of electricity mixes develop according to the reference scenarios of the European Commission and the IEA.

The GaBi software and databank is used for 2015 and 2030 CO_2-intensities of electricity mixes (thinkstep, 2018). As the 2015 electricity mixes could not be obtained from the databank anymore, the 2016 mixes are used instead. In the databank, projections of electricity mixes are available for 2030 only. The projections for the EU are based on the reference scenario of the EU Energy sector by the European Commission (European Commission, 2013). In this scenario, the composition of EU electricity mixes is modelled according to already adopted policies. Projections for the US and CN are based on the "New Policies Scenario" provided by IEA in the latest available World Energy Outlook which entails CO_2-reduction targets already announced by governments (IEA, 2019b). The 2025 CO_2-intensities of electricity mixes are linearly interpolated between the 2015 and 2030 data points. If the calculated annual decrease of kg CO_2 per kWh is extrapolated from 2030 to 2050, the US electricity mix would cause negative emissions, i.e. more CO_2 would be bound than caused. As this is deemed unlikely, the projected development of CO_2 emissions in the power sector provided in the report "Energy Technology Perspectives" 2017 by the IEA are used as additional source (IEA, 2017b). Between 2030 and 2050, the IEA projects a decrease of CO_2 emissions of the power sectors of 31% in the EU, 9% in the US and 21% in China in their RTS scenario which resembles the assumptions of the "New Policies Scenario". These percental changes are used to extrapolate CO_2 emissions per kWh in the three markets based on the 2030 CO_2-intensities provided in the GaBi database. The applied parameters are shown in Table 42.

Table 42 Projected as well as inter- and extrapolated CO_2-intensities of electricity mixes.

Market	CO_2-intensities of electricity mixes [kg CO_2/kWh] per year			
	2016 (used for 2015)	2025	2030	2050
EU	0.46	0.36	0.30	0.09
US	0.62	0.41	0.30	0.03
CN	0.97	0.74	0.61	0.13
Source	(thinkstep, 2018)	Linearly interpolated	(thinkstep, 2018)	Based on percental change 2030-2050 projected by IEA (2017b)

(11) "Scope 3 other categories" are constant.

Above, "scope 3 other categories" (categories 2-7; 10; 13-14) were not identified as main emission drivers for OEMs. As no reduction targets were publicly proclaimed for these categories, they are therefore assumed to be constant based on 2015 values.
Group carbon emissions caused by these "other categories" in 2015 amounted to 24,260,693 t CO_2 (VW, 2017b). VW Group global LDV sales in 2015 are indicated with 9,374,000 (VW, 2016b). Hence, the resulting input parameter is 2.6 t CO_2/vehicle.

(12) In-house production emissions develop according to VW Group target.

In-house production is no main emission driver for OEMs, either. However, a scope 1-2 specific CO_2 reduction target of -45% between 2010 and 2025 was proclaimed (VW, 2017c). 2015 Scope 1 and 2 emissions amounted to 9,210,000 t CO_2 (VW, 2017b). The same LDV sales as in assumption (11) are applied to calculate this input parameter. Assuming 2015 emissions are according to a linear reduction, the according annual reduction of 3% of 2015 emissions is applied to calculate targeted in-house production emissions in 2025. In other words, 2025 emissions equal 70% of 2015 emissions. Likewise, 2030 emissions are assumed to equal 55% of 2015 emissions. The respective values are depicted below. After reaching 0.1 t CO_2/vehicle in-house-production emissions are assumed to remain constant as no or negative emissions from production sites can only be reached with compensation measures which are not eligible for SBT-approved reduction targets.

Table 43 In-house-production emissions per vehicle 2015-2050.

Year	In-house-production emissions [t CO_2/ vehicle]	Source
2015	1.0	(VW, 2017b, 2017c)
2025	0.7	70% of 2015 emissions.
2030	0.5	55% of 2015 emissions.
2050	0.1	Assumption

5.1.5 Scenario 1: Business-as-usual (BAU)

Scenario 1 (S1) acts as the baseline resp. Business-as-Usual (BAU) scenario (see Figure 33). All input parameters develop corresponding to the default input parameters described above. S1 represents an optimistic BAU scenario as one of the main input parameters (CO_2 intensity of electricity mixes) is expected to develop according to the included regions' stated carbon reduction goals for the energy sector. It does not include reduction measures nor mobility services.

5.1.6 Scenario group 2: Reduction measures

In scenario 2 (S2) (see Figure 33) the reduction measures with the most effective CO_2-reduction potentials at the vehicle level are modelled on fleet level. In S2, the effect of renewable electricity sources for LIB production and for PHEV and BEV use phase are computed. The reduction measures are assumed to be operationalised between 2025 and 2050 by all brands in all markets. Subsequently, in Scenarios 2a and 2b, either one of the reduction measures is modelled on its own. All input parameters except the CO_2-intensity of electricity mixes equal the default input parameters. Thus, in S2, both LIB production and electrified vehicles' use phase are connected to the renewable electricity sources module (Figure 34).

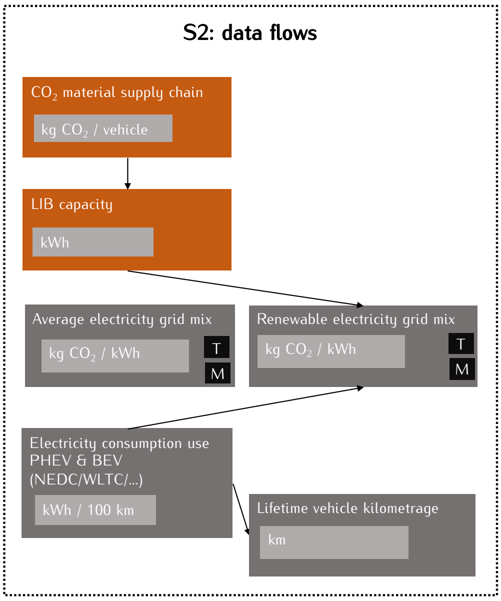


Figure 34 S2: Both LIB production and BEV & PHEV use phase are connected to market- and time-specific renewable electricity module. See Figure 27-Figure 30 for a complete overview of the CBC method.

For electricity originating from 100% renewable sources, GaBi databank CO_2-intensities of wind energy are used (Table 44). These parameters are used to model LIB production and electrified vehicles' use phase emissions in 2025, 2030, 2050.

Table 44 CO_2-intensities of wind energy for EU, US and CN in 2018.

Market	**2018 CO_2-intensity of wind energy [kg CO_2/kWh]**	**Source**
EU	0.00856	(thinkstep, 2018)
USA	0.00617	
CN	0.0127	

Green LIB production

In scenario 2a, (S2a) (see Figure 33) only LIB production between 2025 and 2050 for all brands and all markets is modelled with the wind-sourced energy parameters provided in Table 44. The remaining input parameters (incl. PHEV and BEV use phase emissions) are modelled with default input parameters (Figure 35).

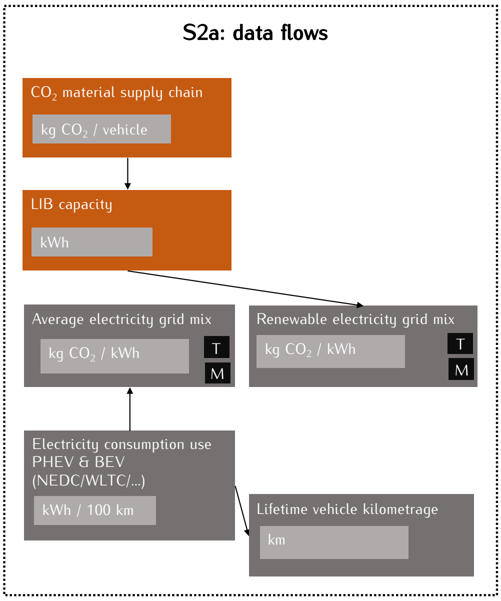


Figure 35 S2a: LIB production is connected to the market- and time-specific renewable electricity module. See Figure 27-Figure 30 for a complete overview of the CBC method.

Green electrified use phase

In scenario 2b (S2b) (see Figure 33), only PHEV and BEV use phase emissions between 2025 and 2050 for all brands and all markets are modelled with the wind-sourced energy parameters provided in Table 44. The remaining input parameters (incl. LIB production emissions) are modelled with default input parameters (Figure 36).

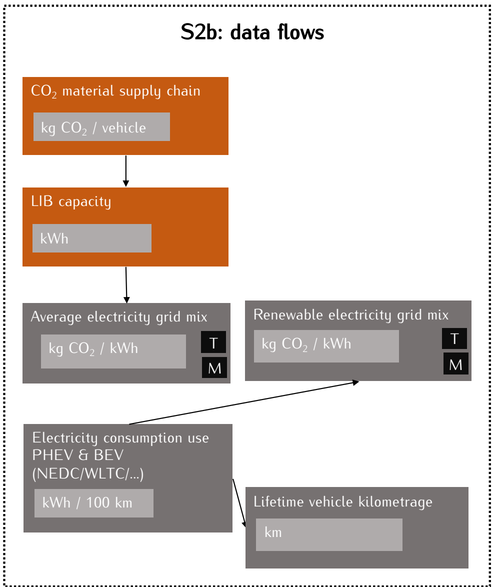


Figure 36 S2b: PHEV & BEV use phase is connected to the market- and time-specific renewable electricity module. See Figure 27-Figure 30 for a complete overview of the CBC method.

5.1.7 Scenario group 3: Mobility services

In scenario 3 (S3) (see Figure 33), demand for mobility services is introduced and its effect on VW Group's fleet size and composition as well as absolute carbon emissions computed. No reduction measures are included. All parameters develop according to the default parameter settings described above. In contrast to prior scenarios, the mobility service module is activated within the CBC method (Figure 37).

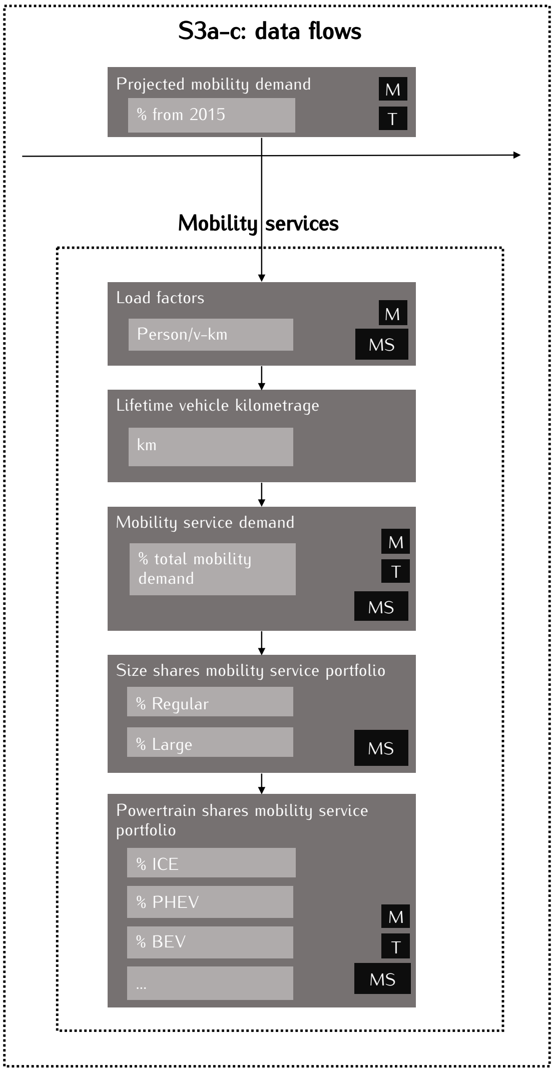


Figure 37 Connected mobility service module in the CBC method in S3a-c. See Figure 27-Figure 30 for a complete overview of the CBC method.

In line with the analysis in 2.3.1, mobility services are expected to increasingly serve personal mobility demand starting between 2021 and 2030 mainly due to legal allowances for autonomous vehicles (PwC, 2017). In S3a-c mobility services are included in the modelling process starting 2030. The market-specific shares of mobility services on total mobility demand served by LDVs in 2030 indicated by PwC (2017) are used as data inputs. As for modelling point 2050 no projections of mobility service shares could be found, it is assumed that 2030 shares double until 2050 (Table 45).

Table 45 Modelled market shares of mobility services on mobility demand provided by LDVs.

Market	Share mobility services on mobility demand for LDVs [%]			
	2015	2025	2030	2050
EU	0	0	25	50
US	0	0	33.5	67
CN	0	0	45	90
Source			(PwC, 2017)	Assumption: doubled 2030-2050

No projections on which specific mobility services will serve the expected general demand for mobility services could be obtained. Therefore, in S3, it is assumed that car sharing, ride hailing and ride pooling each serve 33% of the modelled overall demand for mobility services (Table 46).

Table 46 Modelled shares of different mobility services on overall mobility service demand in EU, USA, CN 2030-2050.

Share mobility service on overall mobility service demand [%]			
Market	Mobility service	2030-2050	Source
EU/USA/CN	Car sharing	33%	Assumption
	Ride hailing	33%	
	Ride pooling	33%	

Load factors for both private vehicles and mobility services are expected to stay constant over time. Therefore, the same load factors are applied throughout the whole modelling timespan. Due to data constraints, the load factors for mobility services are expected to be the same across markets. An overview of these load factors is provided in Table 47, according to the analysis in Chapter 2.2.3. The adopted ride pooling load factor of 2.3 persons per v-km computed by ITF (2018) was chosen because a six-seater vehicle was used as reference model in the study. This resembles the current six-seater MOIA ride pooling vehicle used in Hamburg, Germany (VW, 2019d).

Table 47 Load factors of private vehicles and mobility services (2015-2050).

Load factors [persons per v-km]			
Mobility form	EU	US	CN
Private vehicles	1.45 (European Environment Agency, 2008)	1.59 (Office of Energy Efficiency & Renewable Energy, 2010)	1.5 (Huo et al., 2012)
Car sharing	1.45	1.59	1.5
Ride hailing	1.8 (Shaheen et al., 2014)		
Ride pooling	2.3 (International Transport Forum (ITF), 2018)		

An empty travel rate of 10% is assumed for ride hailing and ride pooling vehicles for all markets and modelling points (Fagnant and Kockelman, 2014). As technical data sheets for specific ride pooling or ride hailing vehicles do not exist yet, curb weights, battery sizes and shares of regular and large vehicles as well as powertrain compositions need to be assumed. An overview is provided in Table 48. Following the ACES trend described above, all mobility service vehicle are modelled as BEVs. Constant in markets and time, the car sharing fleet is assumed to comprise the same shares of regular and large vehicles with respective curb weights as the VWP fleet. The ride hailing fleet is modelled as regular-sized vehicles only with a curb weight matching the VWP average regular curb weight. The ride pooling fleet is computed with 100% large-sized vehicles matching the VWP average curb weight. Battery sizes with respective electricity consumptions are modelled according to the configurations of reference vehicles described in the default parameters section.

Table 48 Mobility services fleets' technical composition across markets and modelling points. Average curb weights according to VWP in Table 35.

Mobility service	**(EU,USA, CN, 2030-2050)**		
	Powertrain	**Shares regular & large vehicles**	**Average curb weights [kg] of regular & large vehicles**
Car sharing	100% BEV	97% regular, 3% large	Regular: 1303, Large: 2036
Ride hailing	100% BEV	100% regular	Regular: 1303
Ride pooling	100% BEV	100% large	Large: 2036

It is possible that the reductive effect mobility services have on vehicle demand is overestimated in this scenario group. Figure 38 shows included and excluded push and pull factors on vehicle demand. Mobility services with higher load factors than private vehicles are a push factor on vehicle demand because more p-km are provided per vehicle. The included pull factor with an increasing effect on vehicle demand is empty travels as these diminish the amount of lifetime p-km provided per mobility service vehicle. In contrast to private vehicles, mobility services are not constricted for children and elderly people who, currently, are not part of projections concerning mobility demand for LDVs. Opening up this new group of customers could boost the demand for p-km provided by mobility services. Likewise, the introduction of mobility services could, in turn, increase the demand for p-km provided by them due to mobility services being affordable and easily accessible (see 2.3.2). However, as the standardised literature review has shown (see 2.4), reliable data on mobility-service related rebound effects is scarce to non-existent. Especially, when considering the geographic scale (markets) and temporal scale (until 2050) applied in this analysis. Authors of the studies assessed in the literature review stated that calculating rebound effects is based on assumptions only, even if mobility services are analysed in a city within a one-year time horizon. Kjaer et al. (2016) highlight that estimating rebound effects for product-service-systems ex ante, i.e. before their market-wide roll-out, puts even higher demands on data quality. As the following scenario analysis is ex ante as well as covering a wide geographical and temporal scale, rebound effects are not included. S3a-c are thus representing a rather positive analysis of mobility services' effects on vehicle demand in terms of CO_2 reduction.

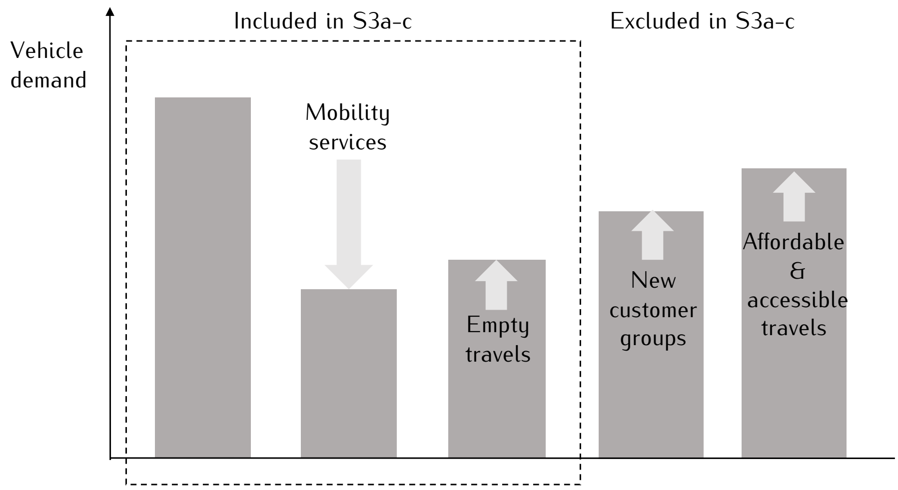


Figure 38 Push and pull factors on vehicle demand included and excluded in S3a-c.

Car sharing

In scenario 3a (S3a) the effect of only using car sharing vehicles to serve the demand for mobility services on VW Group's carbon emissions is modelled. Therefore, the only difference to S3 is that ride hailing and ride pooling vehicles are not included. Projected and assumed overall demand for mobility services is computed according to Table 45. Car sharing vehicles are assumed to provide 100% of overall demanded p-km of mobility services in all markets between 2030 and 2050 (Table 49). As explained in 2.3.1, rates of car sharing vehicles replacing private vehicles are not included in the analysis as this perspective does not take into account needed production volumes to satisfy a given mobility demand, that is, the OEM's perspective.

Table 49 Assumed mobility service shares on overall mobility service demand in S3a.

Share mobility service on overall mobility service demand [%]			
Market	**Mobility service**	**2030-2050**	**Source**
EU/USA/CN	Car sharing	100%	Assumption
	Ride hailing	0%	
	Ride pooling	0%	

Ride hailing
In scenario 3b (S3b) the effect of only using ride hailing vehicles to serve the demand for mobility services on VW Group's carbon emissions is modelled. Projected and assumed overall demand for mobility services is computed according to Table 45. Ride hailing vehicles are assumed to provide 100% of overall demanded p-km of mobility services in all markets between 2030 and 2050 (Table 50). Ride hailing vehicles' technical configuration is modelled according to Table 48.

Table 50 Assumed mobility service shares on overall mobility service demand in S3b.

Share mobility service on overall mobility service demand [%]			
Market	**Mobility service**	**2030-2050**	**Source**
EU/USA/CN	Car sharing	0%	Assumption
	Ride hailing	100%	
	Ride pooling	0%	

Ride pooling
In scenario 3c (S3c) the effect of only using ride pooling vehicles to serve the demand for mobility services on VW Group's carbon emissions is modelled. Projected and assumed overall demand for mobility services is computed according to Table 45. Ride pooling vehicles are assumed to provide 100% of overall demanded p-km of mobility services in all markets between 2030 and 2050 (Table 51). Ride pooling vehicles' technical configuration is modelled according to Table 48.

Table 51 Assumed mobility service shares on overall mobility service demand in S3c.

Share mobility service on overall mobility service demand [%]			
Market	**Mobility service**	**2030-2050**	**Source**
EU/USA/CN	Car sharing	0%	Assumption
	Ride hailing	0%	
	Ride pooling	100%	

5.1.8 Scenario 4: Mobility services & reduction measures

Scenario 4 (S4) (see Figure 33) combines S2 and S3. The assumptions and data inputs of S3 concerning future demands for certain mobility services are linked with the renewable energy module for LIB production and PHEV and BEV use phase of S2 (see Figure 34 and Figure 37). As such, the joint effect on VW Group's absolute carbon emissions by actively pursuing two major reduction measures while serving the projected market demand for private vehicles and mobility services is computed.

5.1.9 Overview of scenario scopes

An overview of scopes covered in the different scenarios is presented in Table 52. Detailed information on input parameters and assumptions is presented in the respective sections above.

Table 52 Overview of scenarios' scopes.

Scenario	Reduction measures	Mobility services
S1	none	none
S2	2025-2050: BEV and PHEV use phase and LIB production with wind energy mixes.	none
S2a	2025-2050: BEV and PHEV LIB production with wind energy mixes.	none
S2b	2025-2050: BEV and PHEV use phase with wind energy mixes.	none
S3	none	2030-2050: car sharing, ride hailing and pooling
S3a	None	2030-2050: car sharing
S3b	None	2030-2050: ride hailing
S3c	none	2030-2050: ride pooling
S4	2025-2050: BEV and PHEV use phase and LIB production with wind energy mixes.	2030-2050: car sharing, ride hailing and pooling

5.2 Model calibration

Before modelling the above described scenarios, the CBC method's ability to compute past year's emissions is evaluated. If past reported scope 1-3 emissions can be re-modelled, it is likely that future emissions are correctly modelled within the described assumptions and conditions. Therefore, both 2015 and 2016 VW Group scope 1-3 emissions are modelled within the CBC method and compared with reported emission figures to CDP. Furthermore, deviations between reported and modelled emissions are explained. Finally, the carbon budget is adjusted according to 2015 modelled absolute VW Group emissions.

5.2.1 With 2015 input data

According to the VW Group's sustainability report, 2015 absolute (i.e. scope 1-3) emissions amounted to 324,785,482 t CO_2 (VW, 2017b). With the indicated input data for 2015 (see 5.1.4), VW Group's absolute emissions in the CBC model result in 284,484,290 t CO_2, i.e. emissions are underestimated by 13.8%. Modelled scope 1-2 emissions (9,210,000 t CO_2) correspond to reported emissions as the 2015 input parameter for "in-house production" (0.98 t CO_2 per vehicle) results from reported scope 1-2 emissions being divided by reported vehicle sales (9,374,000) in the same year. Correspondingly, non-specifically modelled "scope 3 other categories" match reported emissions of these categories (24,260,693 t CO_2) because they are also divided by 2015 reported vehicle sales (VW, 2017b).

Scope 3 category 1 emissions, i.e. material supply chain emissions, are underestimated by 7%: 2015 reported cat. 1 emissions amount to 55,980,353 t CO_2 (VW, 2017b) whereas modelled cat. 1 emissions result in 52,200,266 t CO_2. A possible reason is that in comparison to a multitude of vehicle LCA studies being used within VW Group's cat. 1 emissions calculation, only six reference LCA studies are being used as input parameters; all of them European models. Although CO_2 intensities per kg curb weight resulting from the reference LCAs are correlated with 2015 sold models' curb weights, it might be possible that European models have lower CO_2-intensities per kg curb weight than US and Chinese models. Unfortunately, no publicly available LCA studies for VW Group's non-European models could be retrieved to test this hypothesis. Likewise, it is possible that the proportionate generic subtraction of scope 1-2 emissions on scope 3 cat. 1 emissions in 2015 (14.2%) from reference LCAs is inappropriately high. It is probable, that specific in-house emissions used in modelling reference vehicles life cycle carbon emissions are lower, i.e. an exaggerated scope 1-2 share on overall production phase emissions is subtracted.

Reported 2015 scope 3 category 11 emissions amount to 233,766,999 t CO_2 (VW, 2017b). Modelled WTW emissions are 18% lower (197,735,070 t CO_2). Again, the main reason is probably that no Chinese and US models are used as reference vehicles. 2015 US legal TTW requirements of 153.8 g CO_2/km (Table 33) are underscored by 22% (resulting in a VW Group TTW fleet average of 125.9 g CO_2/km). Likewise, the modelled VW Group Chinese fleet average (120.9 g CO_2/km) underscores the Chinese legal requirements by 33% (161.0 g CO_2/km, see Table 33). It is therefore likely, that VW Group US and Chinese models have higher average TTW emissions than assumed in the model. The modelled 2015 Group EU TTW fleet average of 123.8 g CO_2/km also underscores 2015 legal EU requirements (130 g CO_2/km, see Table 33) by 5%. Either the chosen reference vehicles, the curb weight threshold of 1,700 kg for regular- and large-sized vehicles or a combination of both are thus responsible for the underestimation of TTW and consequently WTW emissions.

Modelled scope 3 cat. 12 emissions, i.e. emissions arising from scrapping or recycling amount to 2,062,280 t CO_2 thus overestimating reported emissions (1,567,437 t CO_2) by 23% (VW, 2017b). A possible reason for this overestimation is that recycling emissions for large reference vehicle were not available. Therefore, differences in curb weights between the respective ICE, PHEV and BEV regular and large vehicles were used to proportionately increase recycling emissions for large reference vehicles. Though apparently, there is no linearly positive correlation between curb weight and recycling emissions as assumed.

5.2.2 With 2016 input data

The same pattern of over- and underestimation can be observed when using 2016 VW data as model input. Below, 2016 input data is described and the modelled absolute emissions compared to reported emissions. As for 2015 data inputs, the information is sourced from the Group annual report and sustainability report (VW, 2017d, 2017b). Again, the provided data is edited to fit the requirements of the used model. Only Group- and brand-specific data is adjusted for 2016. Underlying energy mixes, fuel CO_2-intensities and reference vehicles are according to the default settings described in 5.1.4.

The total figure of globally sold LDVs in 2016 is 9,729,000. This number includes sales by VW, AUDI, ŠKODA, SEAT, PAG, VWN, BENTLEY and VW China (the VW Group’s Joint Ventures (JV) in which brands active in Asia partially sell their vehicles). As for 2015, in order to distribute BENTLEY’s and VW China’s vehicles among the six brands, first brands’ shares on LDV sales without VW China are calculated.

Table 53 Brands' 2016 LDV sales without VW China (VW, 2017d).

Brand	Brand sales 2016 w/o VW China [Volumes]	Share [%]
VWP	4,347,000	55
AUDI	1,534,000	19
ŠKODA	814,000	10
SEAT	548,000	7
PAG	239,000	3
VWN	478,000	6
Sum	7,960,000	100

Based on the brands' Group fleet shares indicated in Table 53, the 9,729,000 globally sold LDVs are redistributed to the brands (Table 54).

Table 54 Brand sales 2016 including VW China redistributed according to shares in Table 53.

Brand	Brand sales redistributed [Volumes]	Share [%]
VWP	5,313,061	55
AUDI	1,874,910	19
ŠKODA	994,900	10
SEAT	669,785	7
PAG	292,114	3
VWN	584,229	6
Sum	9,729,000	100

Brands' market coverages are given for the four markets mentioned above. South American market shares (4% on Group level in 2016) are redistributed to the other markets the respective brand is active in. Depending on the brand, South American market shares are redistributed to either the two or three markets the brand is covering. The resulting market shares are depicted in Table 55.

Table 55 Brands' market shares 2016. South American market shares were redistributed to the respective markets each brand is covering.

Brand	EU share [%]	USA share [%]	CN share [%]
VWP	33.5	11.6	54.9
AUDI	49.0	14.1	36.8
ŠKODA	69.8	0.05	30.3
SEAT	93.9	6.1	0.0
PAG	36.6	26.8	36.6
VWN	89.2	4.1	6.8
Sum	100	100	100

For each brands' model indicated in the 2016 annual report, the highest indicated curb weights provided in the models' technical data sheets were selected to classify for "regular" or "large"-sized vehicles. As for 2015, regular-sized vehicles were defined as weighing up to 1,700 kg, large-sized vehicles as weighing more than 1,700 kg. For each brand average sales-weighted curb weights of "regular" and "large" vehicles are calculated (see Appendix Table 67-Table 72). An overview of brands' size shares with respective curb weights is provided in Table 56.

Table 56 2016 Brands' shares of regular and large vehicles with respective average curb weights. The underlying model-specific curb weights are listed in Appendix Table 67-Table 72.

Brand	Share regular [%]	Share large [%]	Average curb weight regular [kg]	Average curb weight large [kg]
VWP	98	2	1,314	2,035
AUDI	39	61	1,354	1,882
ŠKODA	99.9	0.1	1,279	1,995
SEAT	93	7	1,244	1,805
PAG	24	76	1,518	2,017
VWN	38	62	1,576	2,334

As for 2015 data, no indication of fleet powertrain mixes were found. Therefore, a 100% share of ICE on Group and brand level is assumed. "Scope 3 other categories" input is calculated based on emissions indicated for the scope 3 categories included in these categories (25,341,432 t CO_2) (VW, 2017b) and the Group LDV sales for 2016 (9,729,000 vehicles) (VW, 2017d). As for 2016, the Group-wide input for "Scope 3 other categories" is 2.6 t CO_2 per vehicle. The final data input that is modified according to 2016 information is "in-house production". The 9,510,000 t CO_2 indicated in VW (2017b) for scope 1-2 emissions are divided by the VW Group LDV sales for 2016 mentioned above. As for 2015, the input for "in-house production" results in 0.98 t CO_2 per vehicle.

As indicated before, modelled 2016 absolute emissions are similarly underestimated compared to 2015 emissions. VW Group's 2016 scope 1-3 emissions as reported in VW (2017b) amount to 337,918,918 t CO_2. Modelled scope 1-3 emissions result in 297,665,196 t CO_2, i.e. 13.5% less than reported. Due to the calculation method and data inputs, modelled emission for "scope 3 other categories" and "in-house production" correspond to reported emissions.

Material supply chain emissions, are again underestimated by 7%. 2016 reported cat. 1 emissions amount to 59,415,034 t CO_2 (VW, 2017b) whereas modelled cat. 1 emissions result in 55,649,880 t CO_2. Reported 2016 Scope 3 cat. 11 emissions amount to 241,679,689 t CO_2 (VW, 2017b). Modelled WTW emissions are again 18% lower (205,184,610 t CO_2). Modelled scope 3 cat. 12 emissions result in 2,140,380 t CO_2 overestimating reported emissions (1,606,582 t CO_2) by 25% (VW, 2017b).

5.2.3 Adjusting the carbon budget

In order to calculate a 2 °C-compatible carbon budget for the following scenario analyses, the requirements by SBTi need to be adjusted to fit the scope of the analysis described in 5.1.1. SBTi asks OEMs to use the transport sector-specific SDA tool to calculate carbon reduction pathways for direct and indirect emissions in line with the Paris Agreement (SBTi, 2019c). However, for using this tool undisclosed data is needed. Therefore, the absolute-based approach by SBTi is applied in this scenario analysis. As such, an exemplary 2 °C-compatible carbon budget is used as reference in the scenarios. When applying the CBC method internally, OEMs can use their specific reduction pathway or carbon budget as input parameter, though.

SBTi's absolute-based approach requires all companies worldwide to reduce absolute carbon emissions of 2010 levels by 49% until 2050, i.e. at least 1.23% of 2010 emissions per year, to support a 2 °C target (SBTi, 2018b). VW Group started publishing its absolute CO_2 emissions in 2012 (334,570,925 t CO_2) (VW, 2012). Hence, 2010 Group absolute emissions must be inferred from emission developments past 2012 to derive 2 °C-compatible annual emissions between 2015 and 2050.

The annual change of absolute emissions (e_a) between 2012 ($OEM_{abs,2012}$) and 2017 ($OEM_{abs,2017}$) reported VW Group emissions is calculated based on equation 5.1. $OEM_{abs,2017}$ amounted to 349,297,811 t CO_2 (VW, 2018a).

$$e_{a,2012-2017} = \frac{OEM_{abs,2017} - OEM_{abs,2012}}{2017 - 2012}$$

(5.1)

The resulting $e_{a,2012-2017}$ amounts to +2,945,377 t CO_2 per year. 2010 absolute Group emissions ($OEM_{abs,2010}$) are calculated as shown below:

$$OEM_{abs,2010} = OEM_{abs,2012} - e_a(2012 - 2010)$$

(5.2)

$OEM_{abs,2010}$ thus amount to 328,680,171 t CO_2. As both 2015 and 2016 Group absolute modelled emissions were underestimated (ue) by ca. 14% (see 5.2.1 - 5.2.2), inferred 2010 absolute emissions are equally adjusted by (ue) to correspond to modelled absolute emissions ($OEM_{abs,2010,ad}$):

$$OEM_{abs,2010,\text{ad}} = OEM_{abs,2010} * (1 - ue)$$

(5.3)

$OEM_{abs,2010,ad}$ thus amounts to 282,664,947 t CO_2. To identify the adequate absolute emission level for the scenarios' starting year 2015 according to SBTi ($OEM_{2DS,2015}$), the required 1.23% annual reduction based on 2010 emission levels is applied to $OEM_{abs,2010,ad}$ to derive a 2 °C-compatible absolute emission level for every year until the final modelling year 2050. The resulting starting year's $OEM_{2DS,2015}$ is 265,281,051 t CO_2.

5.2.4 Discussion of model calibration

The comparison of modelled absolute emissions for 2015 and 2016 showed that the CBC method works in a consistent way. Data inputs for different years derived from the same sources and modelled with the same underlying assumptions result in an underestimation of ca. 14% of reported emissions. Not only are absolute emissions underestimated to congruent degrees, but also the single life-cycle phases resp. scopes and categories according to the GHG Protocol. The poor quality of input data used for re-modelling VW Group's past 2015 and 2016 emissions should be considered at this point: although only six reference vehicle LCAs were used, VW China's vehicle sales were re-distributed to the six major brands without further information and the curb weight threshold of 1,700 kg between regular and large vehicles was simply determined by the author, there is only a 14% difference between modelled and reported emissions. This, under the circumstances, comparatively low deviation from specifically calculated emissions based on internal data shows that OEMs' past-emission calculation methodologies analysed in 2.2.1 were adequately transferred into the CBC method.

5.3 Results of scenario analysis

In order to model the scenarios described above, the underlying computational procedures of the CBC method listed in Chapter 4 were transferred into MS Excel (2016). Evaluation of results on Group, brand and market level for both absolute emissions (t CO_2) and relative emissions (t CO_2 per vehicle) is possible in this format of implementation. Likewise, distinguishing between the applied life-cycle phases (a) supply chain, (b) in-house production, (c) WTT, (d) TTW, (e) recycling and (f) "scope 3 other categories" is feasible. In the following, modelling results on these different aggregation levels are presented depending on their respective informational value in each scenario.

5.3.1 Scenario 1: Business-as-usual (BAU)

In S1 absolute scope 1-3 emissions between 2015 and 2050 of the VW Group add up to 11,106,553,069 t of CO_2. The Group's 2 °C-compatible carbon budget of 7,371,195,148 t CO_2 between 2025 and 2050 is thus overshot by 34% (see Figure 39). Combined vehicle sales in EU, USA, CN are computed as 11,459,052 in 2025, 12,510,845 in 2030 and 17,130,053 in 2050. Absolute emissions are modelled as follows: 285,484,290 t CO_2 in 2015, 351,809,389 t CO_2 in 2025, 356,066,968 t CO_2 in 2030 and 223,045,901 t CO_2 in 2050.

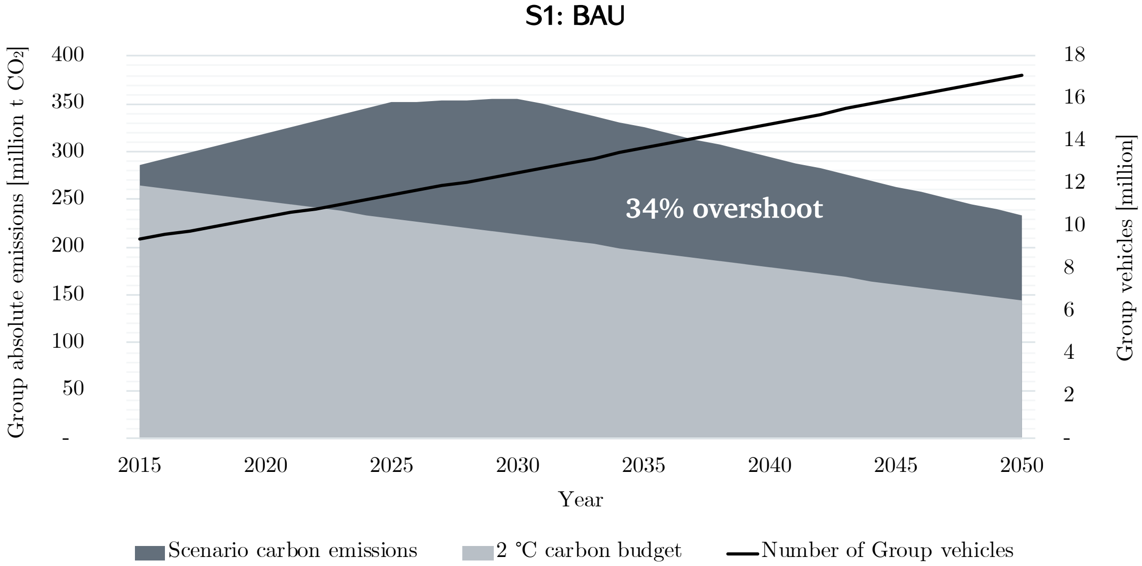


Figure 39 S1: Absolute emissions of VW Group with respective number of sold vehicles.

The reasons why absolute emissions are decreasing after 2030 although vehicle sales are rising can be explained with Figure 40: although electrification of fleets increased from 0% in 2015 to 30-40% BEVs in 2025, 2025 CO_2 relative emissions slightly increase from 30.5 t CO_2 per vehicle in 2015 to 30.7 t CO_2 per vehicle. Both 2025 supply chain and WTT emissions increase compared to 2015 due to CO_2-intensive electricity mixes used for LIB production and electrified vehicles' use phase. Hence, achieved TTW emission reductions due to higher shares of electrified vehicles are almost completely shifted to other life-cycle phases. The budget overshoot is most pronounced between 2015 and 2030 due to a high share of ICEs in the fleets and first shares of electrified vehicles being produced which are charged with CO_2-intensive electricity mixes. In 2030 relative emissions decrease to 28.5 t CO_2 per vehicle. Here, both the effect of less CO_2-intensive electricity mixes for LIB production and use phase as well as increasing shares of BEVs (up to 57% in CN) can be observed as supply chain and WTT relative emissions nearly do not change between 2025 and 2030. TTW emission decrease from 11.4 t CO_2 per vehicle in 2025 to 7.9 t CO_2 per vehicle in 2030.

The assumed 100% BEVs in all markets in 2050 are reflected in missing TTW emissions. WTT emissions per vehicle are markedly lowered to 2.4 t CO_2 per vehicle due to less carbon-intensive electricity mixes in all markets. Supply chain emissions, however, are only reduced by 0.3 t CO_2 per vehicle between 2030 and 2050. Even though LIB production becomes less CO_2 intensive in 2050 (1.2 t CO_2 per vehicle for a 95 kWh LIB in 2050 compared to 3.9 t CO_2 per vehicle in 2030), the supply chain emissions of the large BEV reference vehicle without LIB (12.1 t CO_2 per vehicle) are still higher than supply chain emission of the large ICE reference vehicle (10.3 t CO_2 per vehicle). Therefore, less CO_2-intensive LIB production is outweighed by increasing shares of BEVs with generally higher supply chain emissions even when excluding the LIB production. Only the LIB production module is directly coupled to the market and time-specific electricity mix module; the CO_2 emissions of the remaining components in the supply chains are kept constant during the whole modelling timespan. Likewise, as described in 5.1.4, emissions caused by other scope 3 categories are computed constantly with 2.6 t CO_2 per vehicle. This highlights the conservative approach taken in this exemplary application of CBC method. Not only LIB production emissions but also emissions arising from e.g. steel and aluminium production or wastewater treatment on the production sites will decrease along with the decarbonisation of the energy sector until 2050. Due to data availability not every single component and process can be related to the respective time and market-specific energy mix.

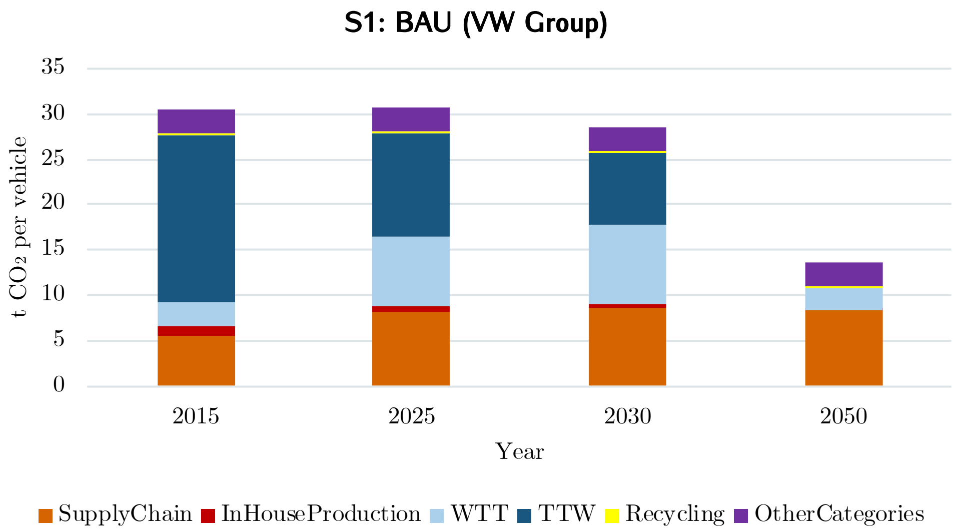


Figure 40 S1: Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

An overview of modelled market and time-specific Group fleet emission averages with respective deviations from legal targets is provided below. In accordance with Table 33, no post-2025 legal requirements in the US nor post-2020 legal requirements in CN could be found. EU, US and CN fleet emission averages partly considerably underscore the legal requirements. As discussed for the 2015 model calibration (see 5.2.1), this is due to only EU reference vehicles being used. The 2 °C-compatible carbon budget was adjusted to this underestimation of TTW emissions (see 5.2.3)

Table 57 Modelled Group fleet emission averages with respective deviation from legal requirements (see Table 33). All fleet emission averages according to NEDC.

Market	Year	Modelled fleet emission average [g CO_2/km]	Deviation from legal requirement [%]
EU	2015	123.8	-5
	2025	76.4	-6
	2030	52.8	-12
US	2015	125.9	-22
	2025	80.7	-20
CN	2015	120.9	-33

Throughout all modelling points, CN has the most CO_2-intensive electricity mixes (see Table 42). In combination with projected highest increases of mobility demand and thus vehicle sales in CN (see Table 30), CN's share on absolute emissions is the highest between 2025 and 2050 (Figure 41).

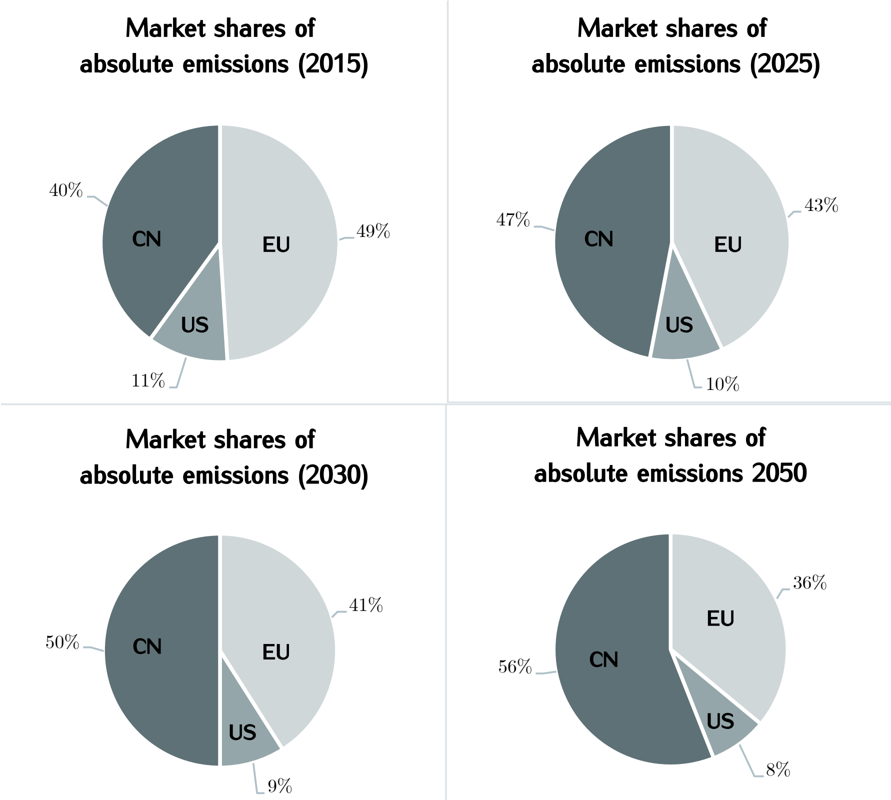


Figure 41 S1: Market shares on VW Group's absolute carbon emissions in 2015, 2025, 2030, 2050.

Additionally, to highlight the dominant role of Chinese electricity mixes on VW Group's absolute emissions, 2025 relative emissions are presented market-specifically in Figure 42. Compared to Group-level WTT emissions in EU (6.1 t CO_2 per vehicle) and in the US (6.6 t CO_2 per vehicle), WTT emissions in CN result in 9.5 t CO_2 per vehicle due to the higher CO_2-intensity of electricity production. As LIB production is assumed to take place in the EU, market-specific differences in supply chain emissions due to used electricity sources do not exist.

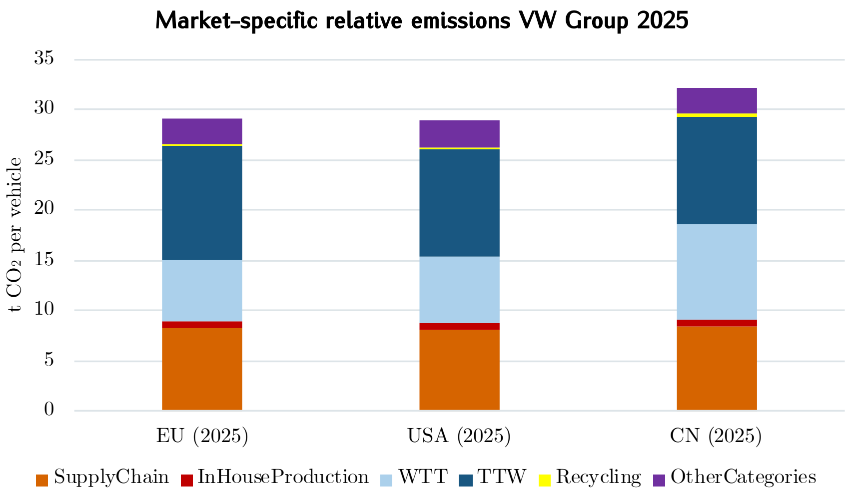


Figure 42 S1: Relative CO_2 emissions on Group level 2025 for EU, US, CN.

VW Group's absolute emissions are composed of brands' absolute emissions. These are, in turn, dependent on their specific product portfolio, i.e. type of vehicles (powertrains, sizes and curb weights), market activities and size of fleet. According to Table 27, VWP's share of total Group sales is 55%, AUDI represents 19% of sales. This general division is also found in brands' shares on the Group's absolute CO_2 emissions (Figure 43). Though AUDI's share on absolute emissions is higher (23%) than their sales shares due to the higher share of large vehicles in their fleet (60%) than VWP (3%) (see Table 35).

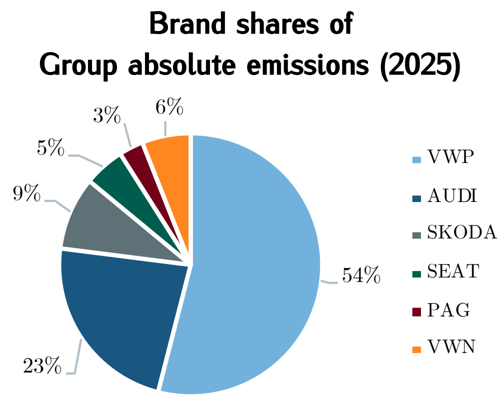


Figure 43 S1: Brand shares on Group absolute CO_2 emissions 2025.

Different compositions of brands' fleets in terms of vehicle sizes and the effect on an average vehicle's life-cycle CO_2-intensity is exemplarily displayed in the following figures. SEAT's fleet is composed of 93% regular sized vehicles with the lowest average Group curb weight of 1,161 kg. Whereas PAG's fleet is composed of 77% large sized vehicles with an average curb weight of 2,017 kg (Table 35). Additionally, SEAT is not selling vehicles in China while PAG sells 35.4% of its vehicles in China (Table 29). This results in lower average carbon emissions per vehicle for SEAT. Figure 44 shows that SEAT's 2030 average vehicle causes 24.5 t CO_2 over its life cycle (Figure 44). In comparison, PAG's average vehicle causes 36.5 t CO_2 over its lifecycle in 2030 (Figure 45).

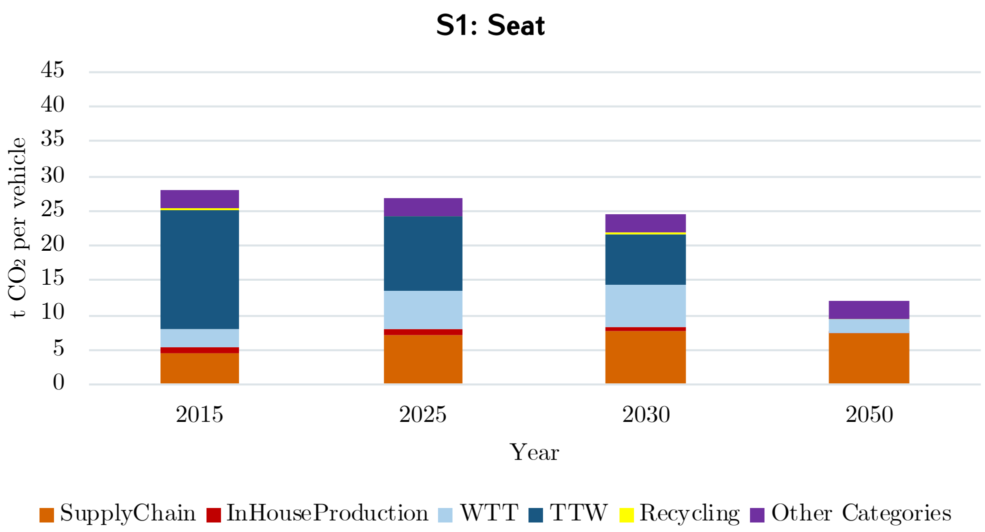


Figure 44 S1: SEAT CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

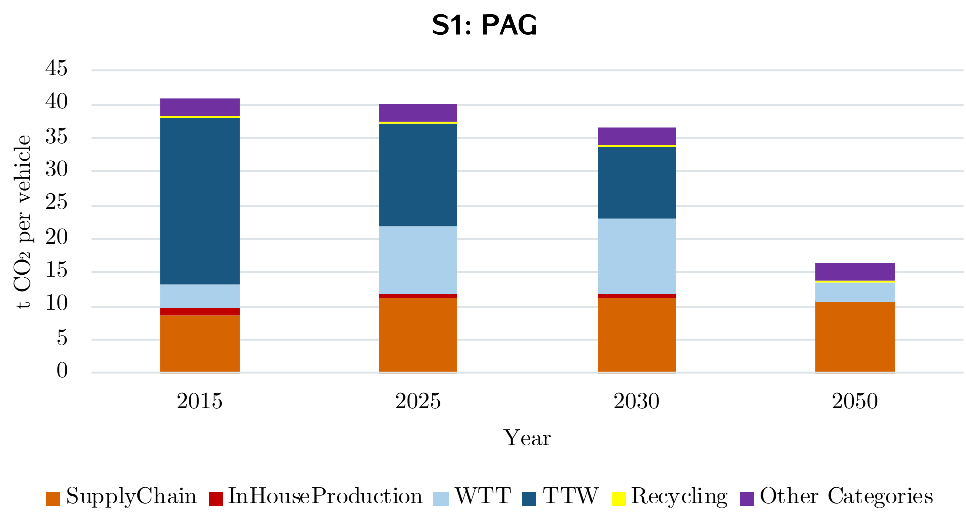


Figure 45 S1: PAG CO_2 emissions per average vehicle 2015, 2025, 2030, 2050.

5.3.2 Scenario 2: Reduction measures

In S2 absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 8,529,055,116 t of CO_2 and are thus 23% lower than S1 absolute emissions. The VW Group's 2 °C-compatible carbon budget is still overshot by 14% (see Figure 46). Combined vehicle sales in EU, USA, CN are computed as 11,459,052 in 2025, 12,510,845 in 2030 and 17,130,053 in 2050. This equals modelled vehicle sales in S1 as no mobility services are included in these scenarios. Absolute emissions are modelled as follows: 285,484,290 t CO_2 in 2015, 271,677,098 t CO_2 in 2025, 251,405,224 t CO_2 in 2030 and 170,186,050 t CO_2 in 2050. Group absolute emissions in 2015 equal emissions in S1 as renewable energy sources used for LIB production and electrified vehicles' use phase are modelled as being implemented in 2025.

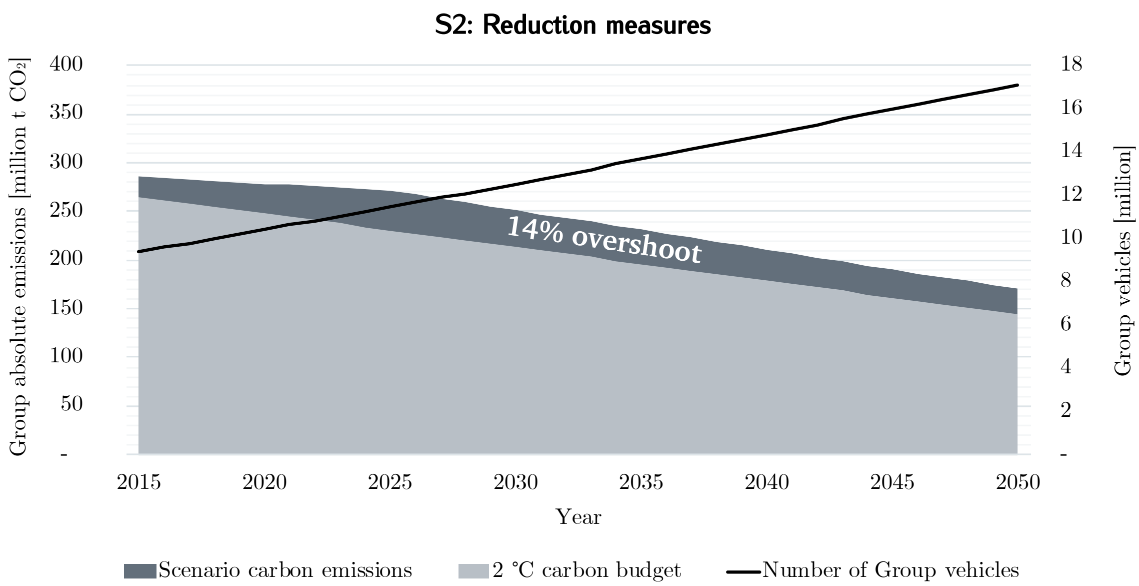


Figure 46 S2: Absolute emissions of VW Group with respective number of sold vehicles.

As vehicle sales projections in S2 equal the sales assumed in S1, the reason for the 20% lower overshoot of the Group carbon budget is lower average life-cycle CO_2 emissions per vehicle (Figure 47). In 2025, compared to S1, S2 WTT emissions are 4.7 t CO_2 per vehicle lower. Likewise, S2 supply chain emissions are 2.2 t CO_2 per vehicle lower. With higher shares of electrified vehicles in 2030, the effect of the two reduction measures is even more pronounced: life-cycle emissions per vehicle are 8.4 t lower in S2 than in S1. CO_2-intensities of electricity mixes assumed in S1 for 2050 have decreased by 87% between 2015 and 2050 in China (see Table 42). Therefore, differences in WTT emissions between S1 and S2 are less pronounced in 2050: S2 WTT emissions are 2.2 t CO_2 per vehicle lower.

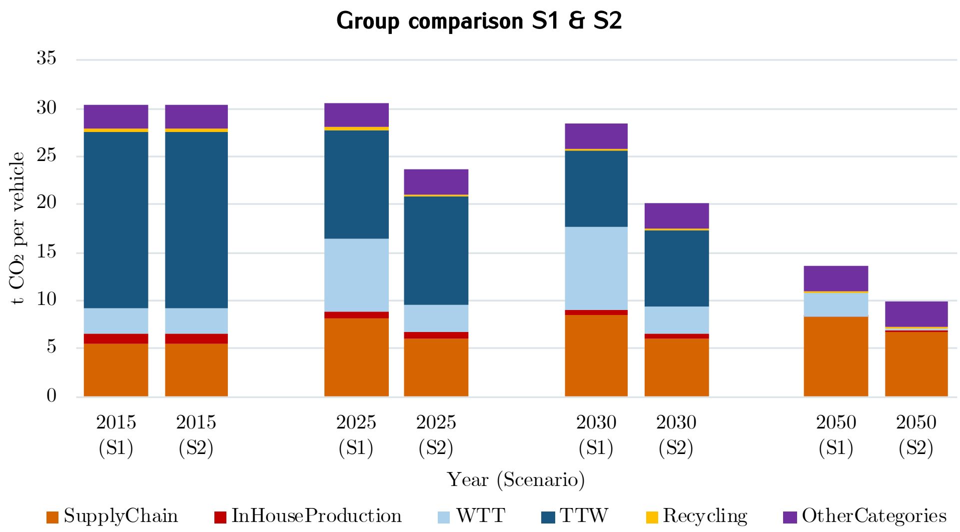


Figure 47 S1 vs. S2: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

The magnitude of reduction effects of these two measures differs among brands. SEAT and PAG represent two extremes of VW Group fleet composition in terms of vehicle size and activity in the CO_2-intensive market CN. Figure 48 and Figure 49 show that the higher the supply chain and WTT emissions are in the baseline scenario the bigger the leverage of the reduction measure. For example, while Seat can reduce WTT emissions in 2025 by 1.5 t CO_2 per vehicle (Figure 48), PAG can reduce WTT emissions by 6.3 t CO_2 per vehicle (Figure 49)with the same reduction measure.

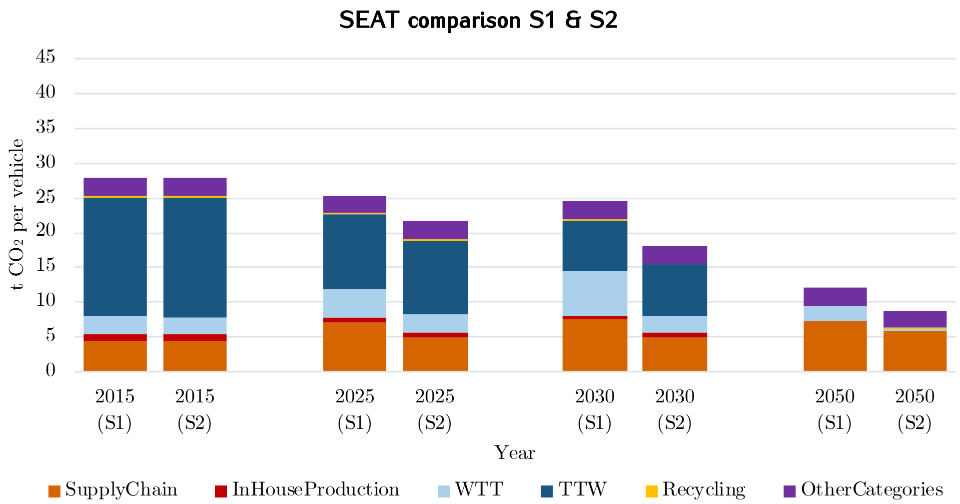


Figure 48 S1 vs. S2: comparing Seat CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

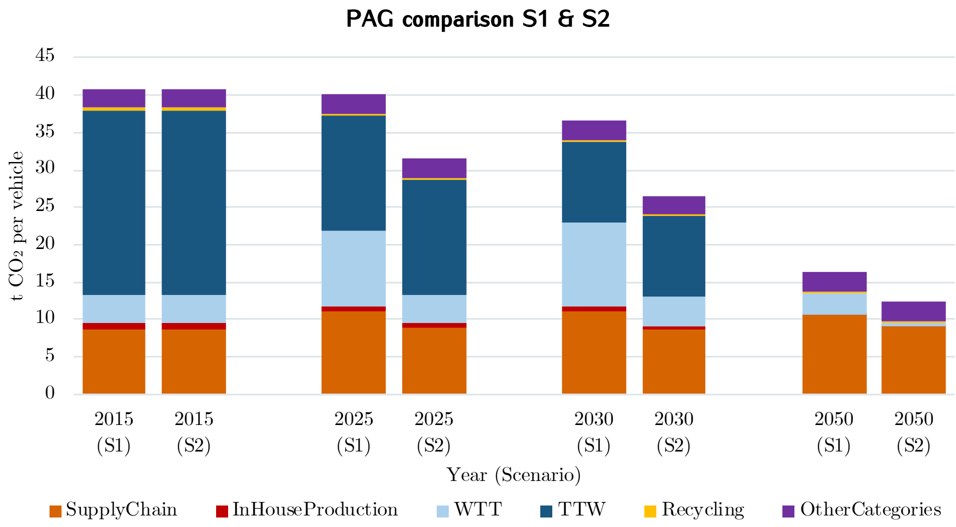


Figure 49 S1 vs. S2: comparing PAG CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.3 Scenario 2a: Green LIB production

In S2a absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 10,238,861,928 t of CO_2. The VW Group's 2 °C-compatible carbon budget is overshot by 28% (see Figure 50). Thus, a 6% lower overshoot compared to S1 is achieved. Combined vehicle sales in EU, USA, CN equal S1 assumptions. Modelled absolute emissions are 326,367,526 t CO_2 in 2025, 323,668,719 t CO_2 in 2030 and 207,150,753 t CO_2 in 2050. Group absolute emissions in 2015 equal emissions in S1.

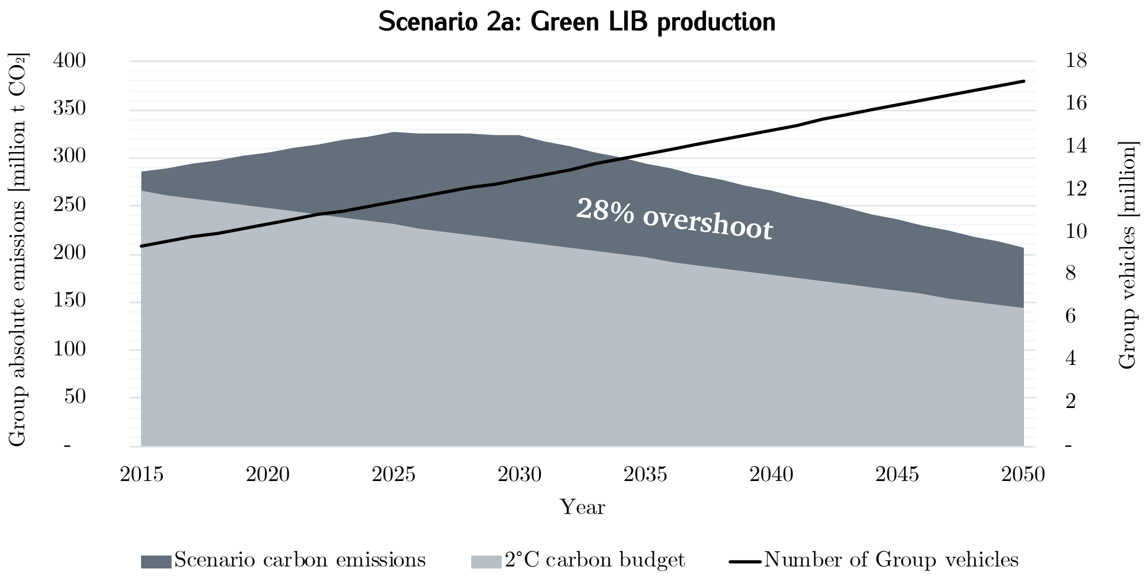


Figure 50 S2a: Absolute emissions of VW Group with respective number of sold vehicles.

The reduction effect of measure "Green LIB production" can be seen in supply chain emissions. Figure 51 shows the same reductions in supply chain emissions as in S2. 2025 Supply chain emissions of S2a are 2.2 t CO_2 per vehicle lower than in S1. In 2030, a supply chain emissions reduction of 2.6 t CO_2 per vehicle and in 2050 a reduction of 1.5 t CO_2 per vehicle is achieved. In S2a, supply chain emissions of 2050 (6.8 t CO_2 per vehicle) surpass 2030 supply chain emissions (5.9 t CO_2 per vehicle) because of the assumed 100% BEV fleet in all markets.

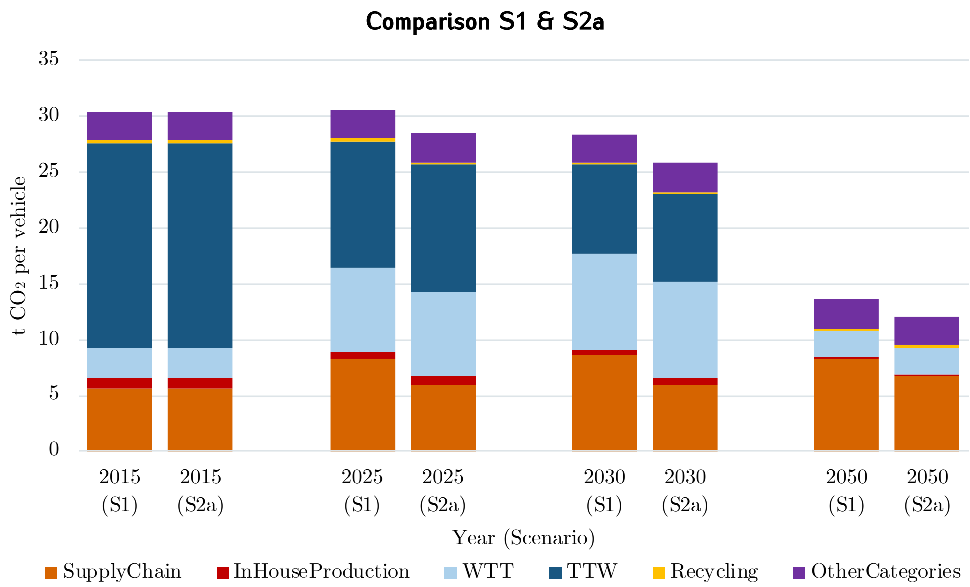


Figure 51 S1 vs. S2a: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.4 Scenario 2b: Green electrified use phase

In S2b absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 9,404,951,769 t of CO_2. The VW Group's 2 °C-compatible carbon budget is overshot by 22% (see Figure 52). Hence, a 12% lower overshoot compared to S1 is achieved. Combined vehicle sales in EU, USA, CN equal S1 assumptions. Modelled absolute emissions are 291,118,962 t CO_2 in 2025, 283,803,472 t CO_2 in 2030 and 196,081,198 t CO_2 in 2050. Group absolute emissions in 2015 equal emissions in S1.

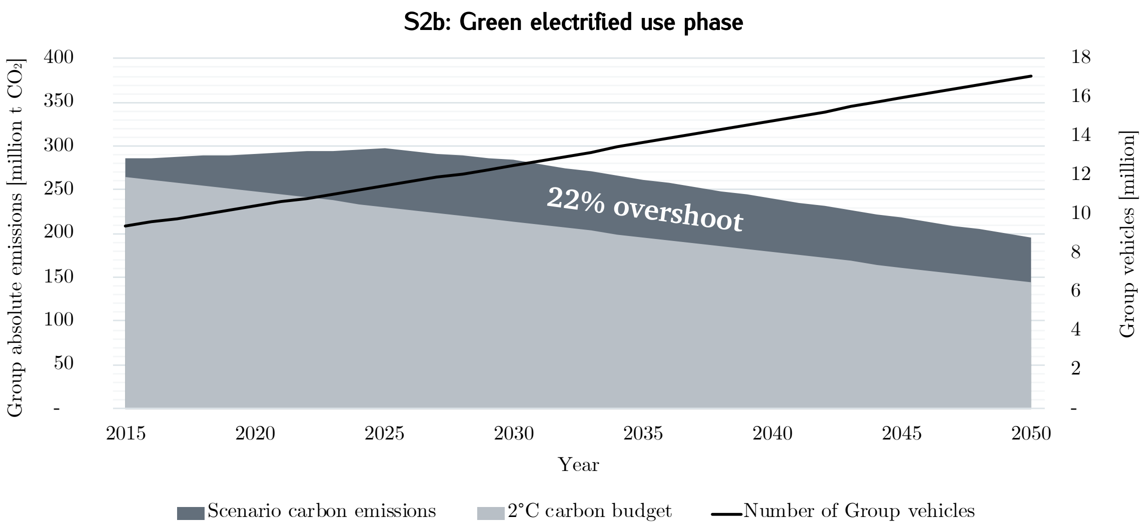


Figure 52 S2b: Absolute emissions of VW Group with respective number of sold vehicles.

The reduction effect of measure "Green electrified use phase" is seen in WTT emissions per average VW Group vehicle (Figure 53). Here, the same reductions in WTT emissions as in S2 are observed. 2025 WTT emissions of S2b are 4.7 t CO_2 per vehicle lower than in S1. In 2030, a WTT emissions reduction of 5.8 t CO_2 per vehicle and in 2050 a reduction of 2.2 t CO_2 per vehicle is achieved. Due to the baseline's electricity mix projected to become less CO_2-intensive until 2050, the modelled reduction of WTT emissions compared to S1 are less pronounced in 2050 than in 2030 although the share of BEVs in all fleets increases.

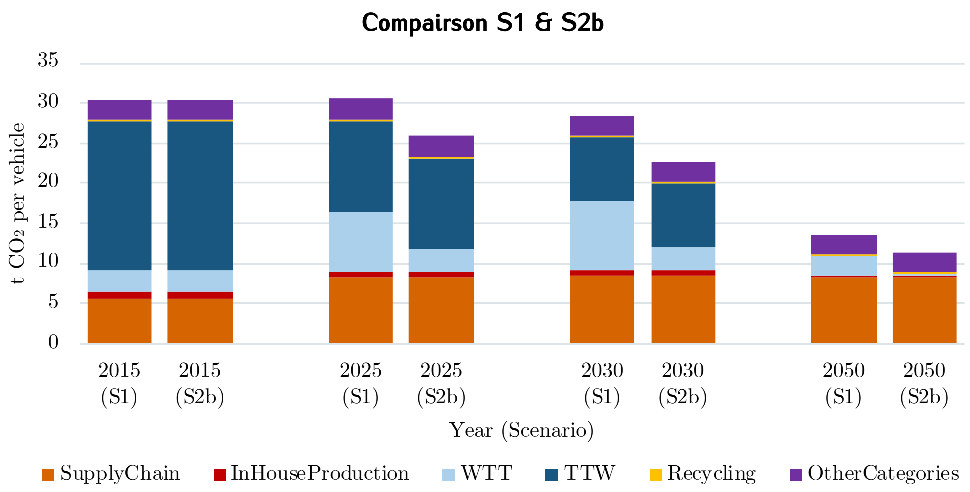


Figure 53 S1 vs. S2b: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.5 Scenario 3: Mobility services

In S3 absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 10,737,144,645 t of CO_2. The Group's 2 °C-compatible carbon budget is overshot by 31% (see Figure 54). A 3% lower overshot of the carbon budget compared to S1 is achieved. Mobility services are modelled to be included in the VW Group's fleets from 2030 onwards. Therefore, combined vehicle sales in EU, USA, CN in 2015 and 2025 equal sales in the baseline scenario (S1). 11,978,379 sold vehicles are computed for 2030 and 15,629,758 in 2050. Hence, in 2030 4% vehicles less are sold than in S1 and 9% fewer vehicles in 2050. Here, the term "sold" includes the mobility services vehicles that remain property of the VW Group. Absolute emissions are modelled as follows: 337,719,372 t CO_2 in 2030 and 220,438,665 t CO_2 in 2050. VW Group absolute emissions in 2015 and 2025 equal emissions in S1.

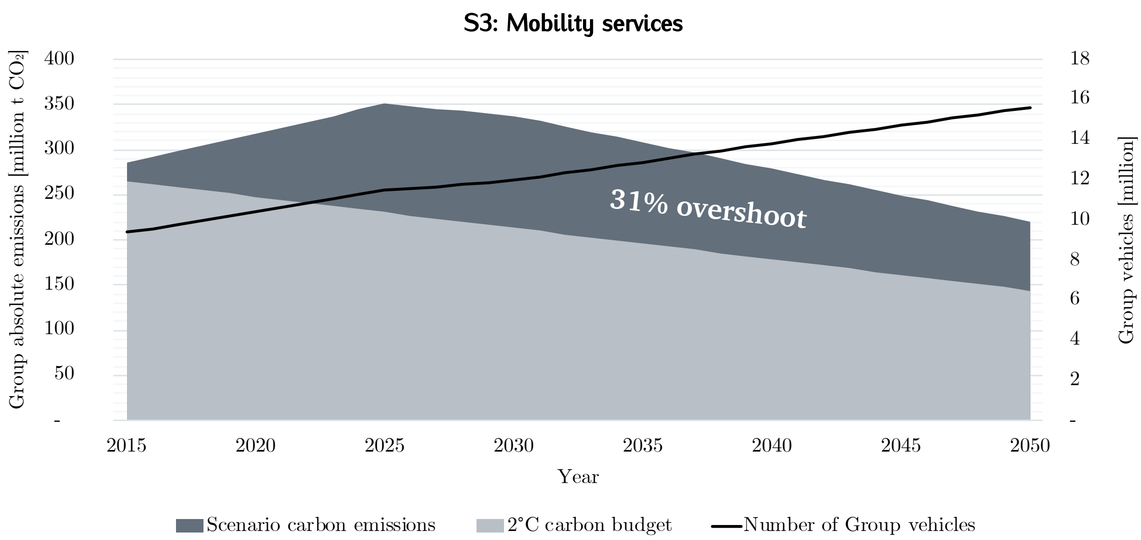


Figure 54 S3: Absolute emissions of VW Group with respective number of sold and mobility service vehicles.

The reason why computed VW Group absolute emissions do not decrease proportionally to the lower number of vehicles modelled in S3 compared to S1 is the different fleet composition and resulting life-cycle CO_2 emissions per average vehicle (Figure 55): a higher share of large electrified vehicles compared to prior scenarios. Starting 2030, fleet electrification shares are increased compared to S1 as mobility service vehicles are assumed to be fully electrified. Therefore, in 2030, WTT emissions are 1.0 t CO_2 per average vehicle higher than in S1. 2030 supply chain emissions are 1.3 t CO_2 per average vehicle higher, respectively.

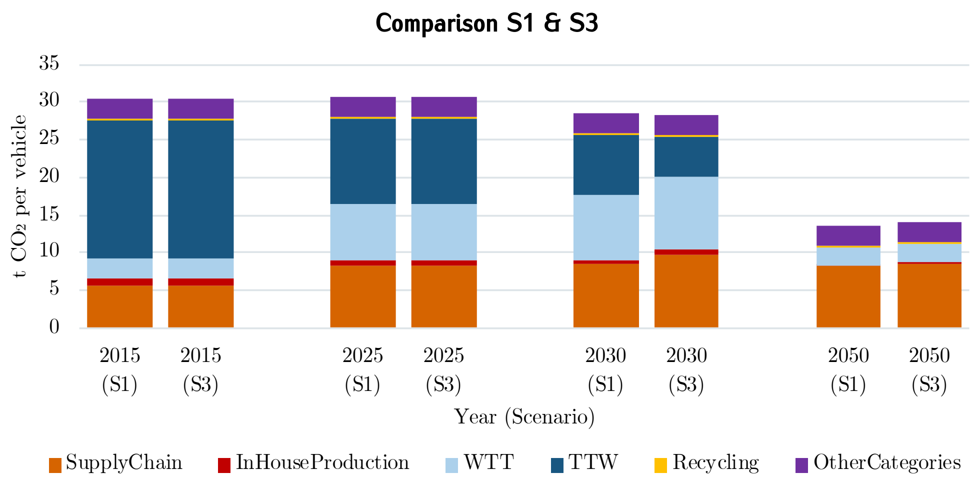


Figure 55 S1 vs. S3: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.6 Scenario 3a: Car sharing

In S3a absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 10,819,620,221 t of CO_2. The Group's 2 °C-compatible carbon budget is overshot by 32% (see Figure 56). Thus, a 2% lower overshoot of the carbon budget compared to S1 is achieved. Since load factors of car sharing vehicles are assumed to be the same as for private vehicles, computed vehicles sales are the same in S3 as in the baseline scenario. Absolute emissions differ from S1 starting 2030. They are computed as follows: 339,976,084 t CO_2 in 2030 and 224,87477 t CO_2 in 2050.

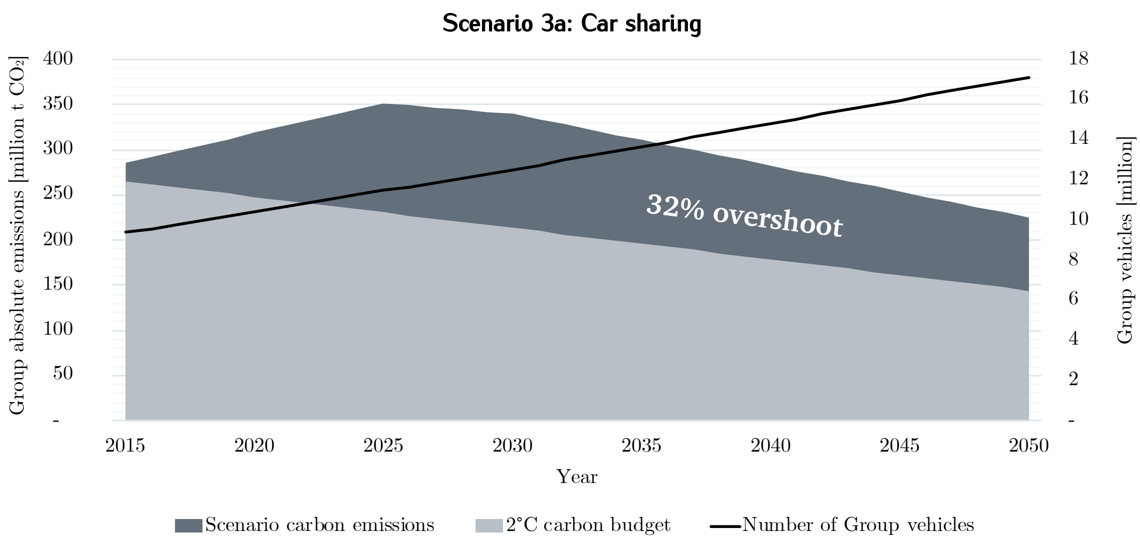


Figure 56 Scenario 3a: Absolute emissions of VW Group with respective number of sold vehicles.

Although the number of vehicles sold and produced in the modelling timespan are the same as in S1, the carbon budget is slightly less overshot due to the earlier onset of fleet electrification. This effect is displayed in Figure 57. Compared to S1, 2030 TTW emissions in S3a are 2.8 t CO_2 per vehicle lower. However, WTT emissions in the same year are 0.5 t CO_2 per vehicle higher. Higher shares of BEVs in the fleets thus lower TTW emissions while WTT emissions are increasing.

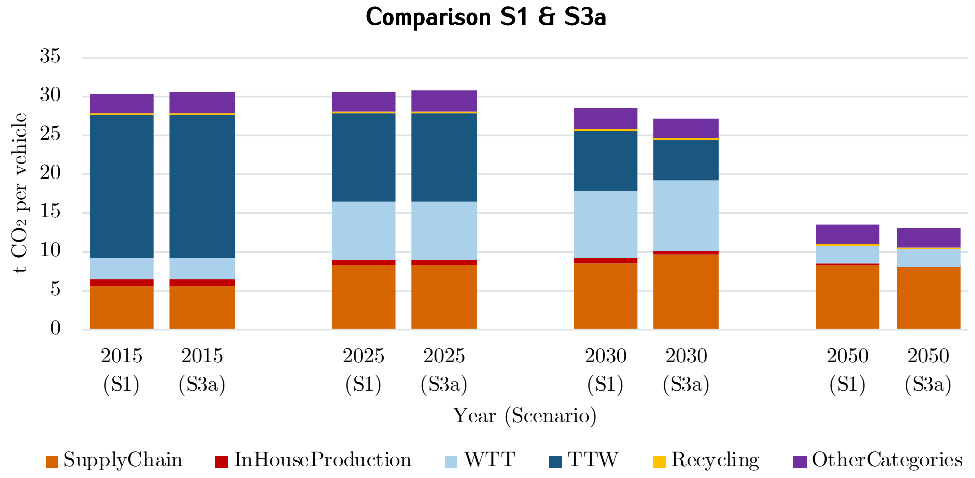


Figure 57 S1 vs. S3a: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.7 Scenario 3b: Ride hailing

In S3b absolute scope 1-3 emissions between 2015 and 2050 of VW Group add up to 10,542,742,144 t of CO_2. The Group's 2 °C-compatible carbon budget is overshot by 30% (see Figure 58). Thus, a 4% lower overshot of the carbon budget compared to S1 is achieved. Absolute emissions start to differ from S1 from 2030 onward. They are computed as follows: 317,415 t CO_2 in 2030 and 210,408,959 t CO_2 in 2050. Since ride hailing vehicles are assumed to have higher average load factors as private vehicles (see Table 47), fewer vehicles are needed to provide the same amount of projected person-km. In 2030 3% fewer vehicles in the EU, US and CN fleets are modelled compared to S1; in 2050 6% less. More vehicles in total are needed to serve the same amount of person-km than in S3 as ride pooling vehicles included in S3 are assumed to have higher average load factors than ride hailing vehicles.

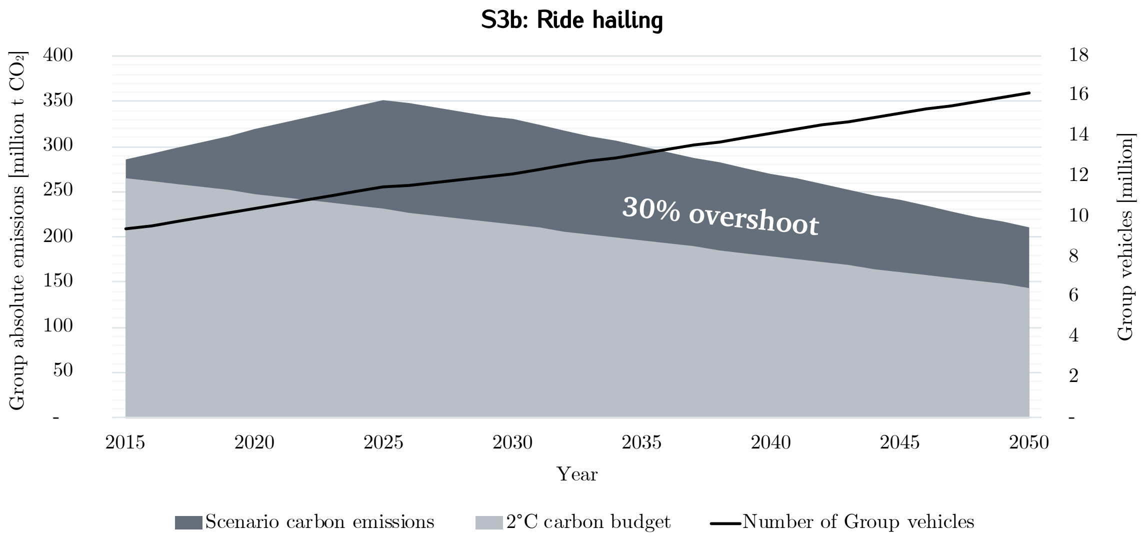


Figure 58 S3b: Absolute emissions of VW Group with respective number of sold and mobility service vehicles.

The lower overshoot of the carbon budget compared to S1 is due to the lower amount of produced and used vehicles as well as the fleet composition. Figure 59 shows Group average vehicle life-cycle CO_2 emissions of S1 and S3b. Due to increased electrification of the fleet in 2030 in S3b, TTW emissions are lower while WTT and supply chain emissions are higher than in S1. In 2050, S3b average vehicle's emissions are lower than in S1 because ride hailing vehicles are assumed to be regular-sized vehicles only (Table 48). Therefore, 2050 supply chain emissions (-0.4 t CO_2 per average vehicle), WTT emissions (-0.2 t CO_2 per average vehicle) and recycling emissions (-0.01 t CO_2 per average vehicle) are lower than in S1.

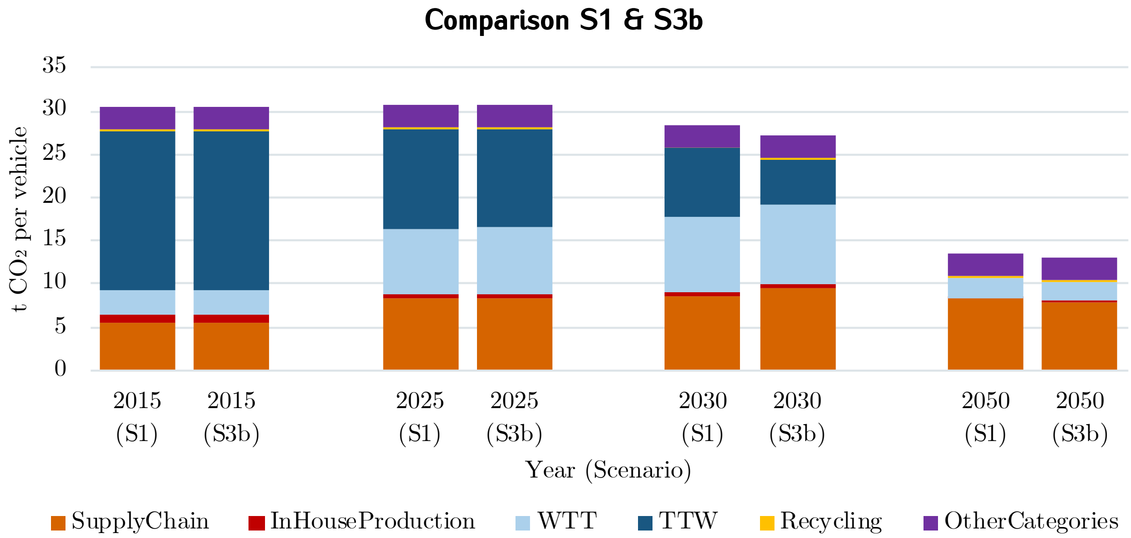


Figure 59 S1 vs. S3b: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.8 Scenario 3c: Ride pooling

Modelled absolute scope 1-3 emissions in S3c between 2015 and 2050 of VW Group add up to 10,872,133,756 t of CO_2. The VW Group's 2 °C-compatible carbon budget is overshot by 32% (see Figure 60). Hence, a 2% lower overshoot of the carbon budget compared to S1 is achieved. Absolute emissions differ from S1 starting 2030. They are computed as follows: 343,204,907 t CO_2 in 2030 and 226,032,230 t CO_2 in 2050. Since ride pooling vehicles are assumed to have the highest average load factors among the included mobility services (see Table 47), the least number of vehicles is needed to provide the same amount of projected person-km compared to the other scenarios. In 2030 10% fewer vehicles in the EU, US and CN fleets are computed compared to S1; in 2050 21% less.

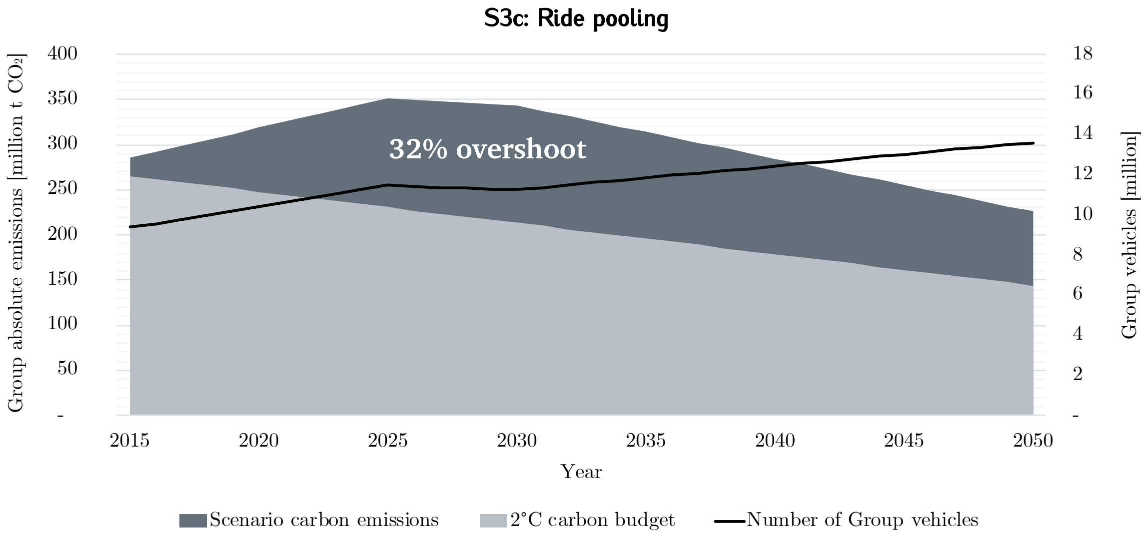


Figure 60 S3c: Absolute emissions of VW Group with respective number of sold and mobility service vehicles.

Although S3c is the scenario in which least vehicles are being produced and used throughout the modelling timespan, it is not showing the lowest carbon budget overshoot. As can be seen in Figure 61, the higher share of large BEVs in the fleet is increasing supply chain and WTT emissions. Compared to S1, 2030 supply chain emissions are 1.9 t CO_2 per vehicle higher (2 t in 2050); 2030 WTT emissions are 2.4 t CO_2 per vehicle higher (0.9 t in 2050) and recycling emission are 0.03 t CO_2 per vehicle higher (0.05 t in 2050).

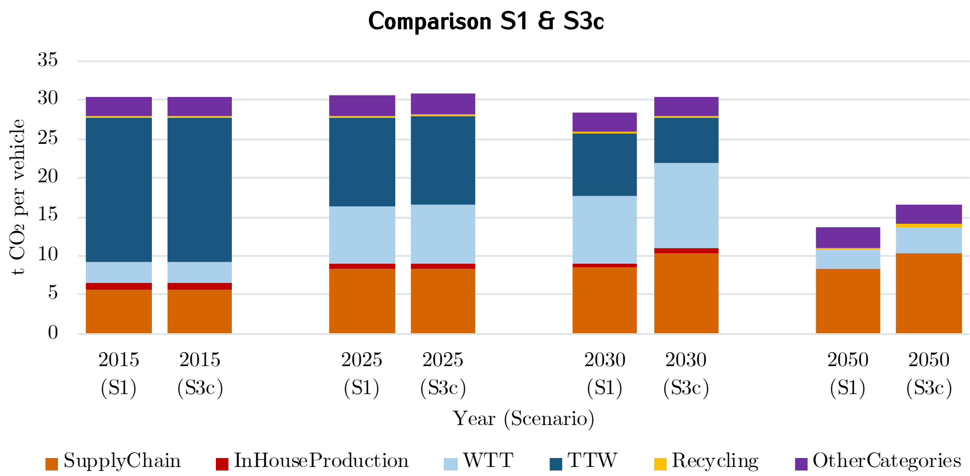


Figure 61 S1 vs. S3c: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.9 Scenario 4: Mobility services & Reduction measures

Absolute scope 1-3 emissions in S4 between 2015 and 2050 of VW Group add up to 7,851,688,726 t of CO_2. Hence, the Group's 2 °C-compatible carbon budget is overshot by 6% (see Figure 62). As S4 is a combination of assumptions of S2 and S3, 2015 absolute emissions equal S1 (285,484,290 t CO_2) and 2025 absolute emissions equal S2 (271,677,098 t CO_2). For modelling points 2030 and 2050 both reduction measures and mobility services are included in the scenario. The resulting absolute emissions are 204,390,843 t CO_2 in 2030 and 160,862,986 t CO_2 in 2050. The overall amount of modelled vehicles produced and used between 2015 and 2050 equals that of S3 (451,342,086 vehicles).

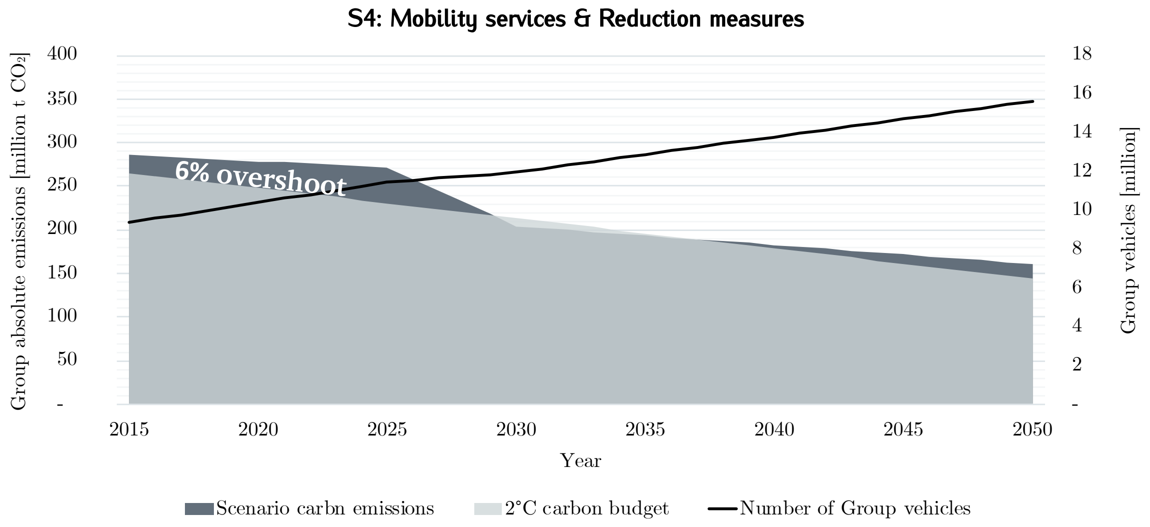


Figure 62 S4: Absolute emissions of VW Group with respective number of sold and mobility service vehicles.

In Figure 63 both the effects of reduction measures and inclusion of mobility services on life-cycle CO_2 emission per average VW Group vehicle are shown. S4 2025 emission per vehicle equal S2 emissions (22.7 t CO_2 per vehicle) equally to modelled absolute emissions. S4 2030 emissions per vehicles are 11.4 t CO_2 lower than S1 emissions in the same year. Reasons are the combination of altered fleet composition due to mobility services and reduction measures in WTT and supply chain phase in S4. While S3 2030 relative emissions are higher compared to S1 2030 relative emissions, here, the same fleet compositions as in S3 causes lower emissions per vehicle compared to S1. The reason is that for increased amounts of LIB production and electricity need for electrified vehicles' use phase only electricity from renewable sources is used. Similarly, in S4, 2050 supply chain emissions are lower by 1.2 t CO_2 per vehicle and WTT emissions by 2.1 t CO_2 per vehicle compared to S1.

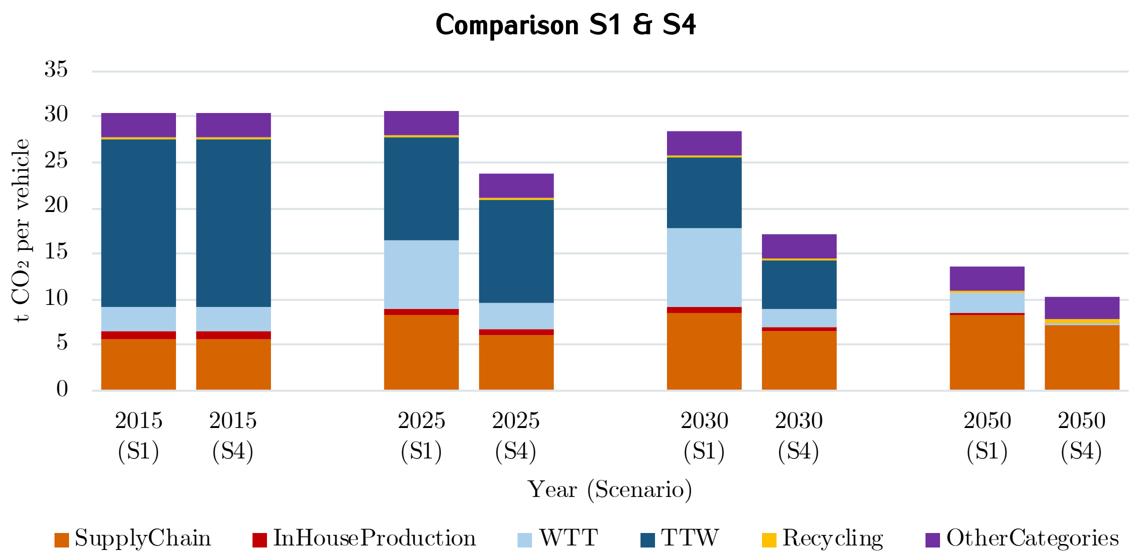


Figure 63 S1 vs. S4: comparing Group CO_2 emissions per average vehicle in 2015, 2025, 2030, 2050.

5.3.10 Additional scenarios

The carbon budget was neither met nor underscored in any of the above scenarios although the effect of high-leverage reduction measures was included. Therefore, two additional scenarios are modelled. The lowest computed overshoot of the carbon budget is 6% facilitated by lowering the number of produced vehicles via mobility services and operationalising renewable energy in LIB production and use phase in S4. This means that both reduction measures and reducing the vehicle amount is key to lower absolute emissions. However, it is still not sufficient to comply with the carbon budget. S3c's results clearly show that it not only matters that vehicle numbers are reduced but also what type of vehicles facilitate this reduction, i.e. the size of those vehicles matters as well. Following these findings, the additional scenarios aim at (a) reducing vehicle numbers, (b) implementing reduction measures and (c) keeping average vehicle sizes as low as possible. Therefore, the additional scenarios 3b* and 3c* compute scenarios 3b and 3c with reduction measures being operationalised as indicated in S2 (Figure 64). As such, it is tested whether the higher vehicle reduction by ride pooling vehicles or the vehicle reduction and reduction of average vehicle size by ride hailing in combination with renewable energy has a higher absolute carbon reduction effect. The additional scenarios with respective modelling results are presented in a shorter format than the original scenarios.

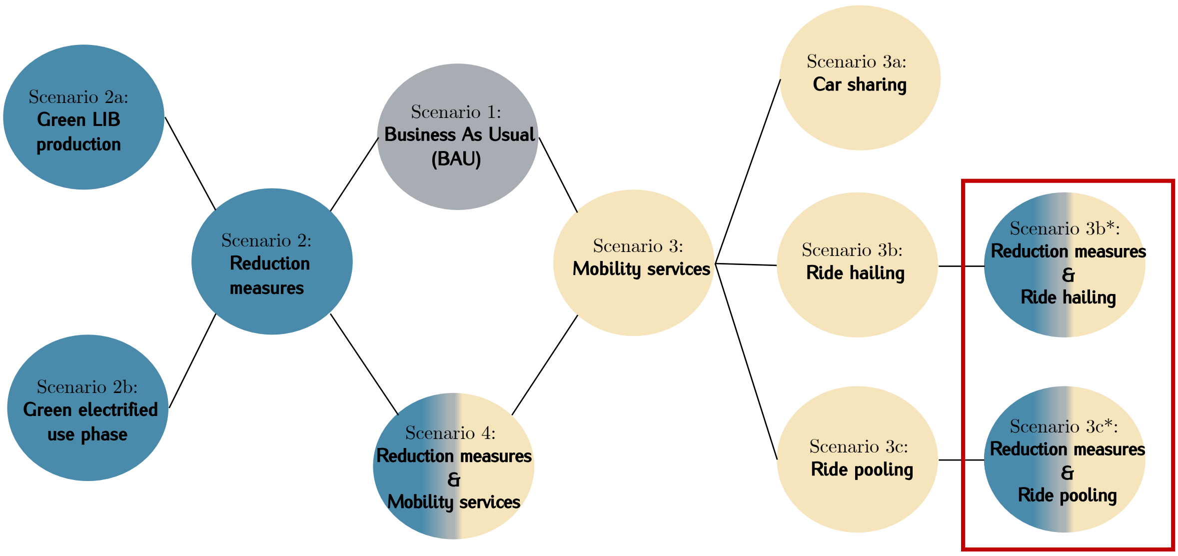


Figure 64 Scenario landscape with additional scenarios 3b* and 3c*.

In S3b* the carbon budget is overshot by 5% (Figure 65). Absolute scope 1-3 emissions in S3b* between 2015 and 2050 of VW Group add up to 7,744,447,536 t of CO_2. Compared to S1, in the whole modelling timespan 3.4 billion t CO_2 less are caused. As S3b* is a combination of assumptions of S2 and S3b, 2015 absolute emissions equal S1 (285,484,290 t CO_2) and 2025 absolute emissions equal S2 (271,677,098 t CO_2). For modelling points 2030 and 2050 both reduction measures and ride hailing are included in the scenario. The resulting absolute emissions are 201,899,464 t CO_2 in 2030 and 153,615,467 t CO_2 in 2050. The overall amount of modelled vehicles produced and used between 2015 and 2050 equals that of S3b.

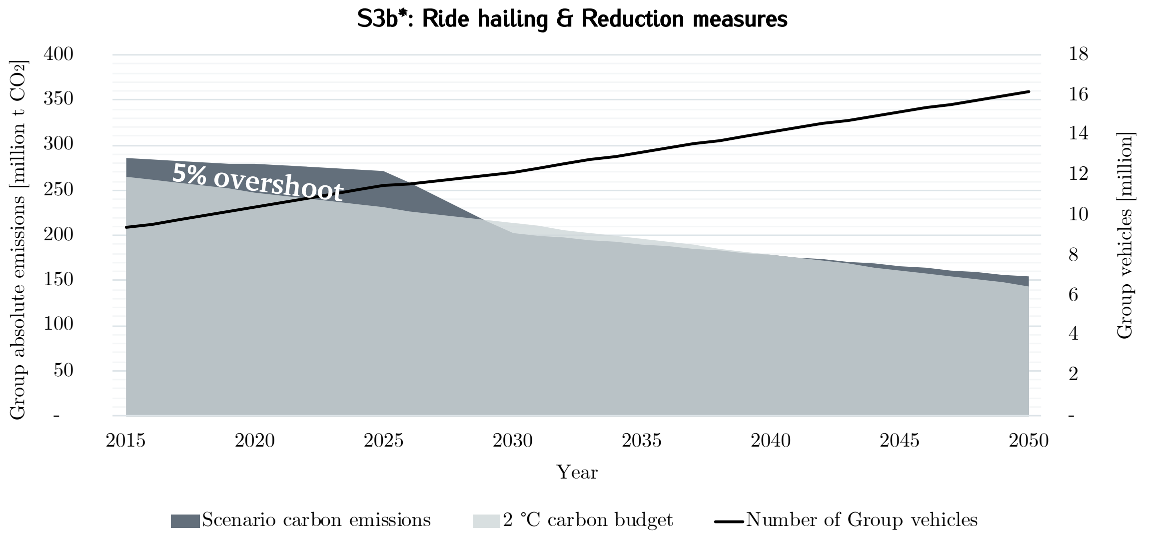


Figure 65 S3b*: Absolute emissions of VW Group with respective number of sold and mobility service vehicles.

In S3c* the carbon budget is overshot by 7% (Figure 66). Absolute scope 1-3 emissions in S3c* between 2015 and 2050 of VW Group add up to 7,906,471,276 t of CO_2. Although between 2030 and 2050 roughly 38 million vehicles less are needed in S3c* than in S3b*, the highest reduction of Group absolute emissions is facilitated in S3b*. These results highlight the above finding that not only the amount of reduced vehicles matters but likewise the type of vehicles replacing private vehicles.

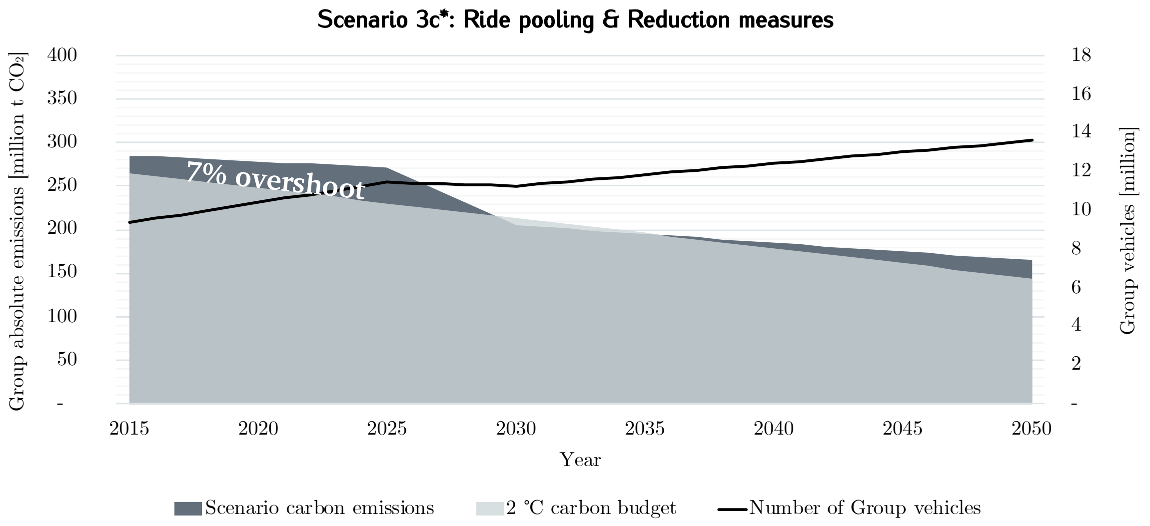


Figure 66 S3c*: Absolute emissions of VW Group with respective number of sold vehicles.

5.4 Sensitivity analysis of results

Within the following sensitivity analysis, the robustness of the scenario analyses' results and respective recommended courses of action are tested by modifying crucial input parameters. Hence, in this chapter, a range of "what if" scenarios are modelled according to the one-at-a-time-approach mentioned by Groen et al. (2014) in which one factor at a time is modified to test its influence on results. According to the guidance provided in 4.12, the recommendations for sensitivity analysis in the ILCD handbook are used (EC-JRC, 2010). Specifically, to focus on testing input parameters which both lack quality and have a high impact on the scenarios' results.

In this sensitivity analysis, the focus is therefore laid on non-VW specific input data. For instance, not the starting year's primary data directly sourced from annual and sustainability reports is modified but generic data from other sources. Neither is VW-specific information derived from technical data sheets on reference vehicles' fuel and energy consumption modified as these figures are based on standardised test cycles.

Specifically modelled key life-cycle phases with a high impact on overall results are emissions caused in supply chain and during use phase. The by far highest impact on the results of scenarios without additional reduction measures has the assumed development of energy intensity of average electricity grid mixes until 2050 (Table 42). In lack of data sources that qualitatively compare to IEA's projections, the default energy emission factors could only be changed within an arbitrary range. It was clearly shown, however, that using renewable energy sources for LIB production and electrified vehicles' use phase are the major reduction measures to be pursued in order to stay within the given carbon budget. Hence, the resulting level when operationalising these reduction measures would be the same, independent of the starting emission levels. In effect, the modelled amount of absolute emissions being reduced would change, though no new statement on target achievement could be made. Therefore, assumed electricity mixes are not included in this sensitivity analysis. The same argumentation holds true for using emission factors of consumption electricity mixes instead of production mixes. According to Eurostat (2019), all EU member states are energy net importers since 2013, i.e. CO_2-intensities of consumption mixes differ from production mixes. The difference of CO_2-intensities between the mixes is, however, irrelevant concerning the statements derived from the above scenario analysis. Using renewable energy sources for LIB production and electrified vehicles' use phase were shown to be the major reduction measures which remains unchanged as CO_2-intensities of either production or consumption average electricity mixes are higher than of e.g. wind energy[3].

Neither are Diesel and gasoline supply chains analysed further as VW Group's strategy concentrates on electrifying their fleets. Starting with their 2018 CDP reporting, VW Group decided to increase the assumed lifetime kilometrage of vehicles from 150,000 to 200,000 km (VW, 2019e). This change of assumptions increases reported use phase emissions. In order to apply the CBC method, it does not matter which lifetime kilometrage is chosen. For the scenario analysis, 150,000 km are used because the starting year's (2015) reported emissions were calculated with this assumption. SBTi's requirement of reducing absolute emissions of 2010 levels by 49% until 2050 to attain a 2 °C target would remain the same independent of the assumed lifetime kilometrage and respective emission level. Therefore, the conclusions drawn from the scenario analyses' results would not change when increasing the lifetime kilometrage by 50,000 km. Remaining high priority input parameters are the assumed energy intensity of LIB production, the development of mobility demand, and mobility service load factors which are analysed below.

3 For up-to-date differences in CO_2 intensities of production and consumption electricity mixes in the EU, America, India and Australia check https://electricitymap.org (accessed 14.08.2019).

5.4.1 Energy-intensity of LIB production

As default setting for the energy-intensity of LIB production the mean of indicated upper and lower electricity requirements of Romare and Dahllöf (2017) was chosen. In the following, both the effect of using the lower and upper indicated value as default setting in S1 on carbon budget compliance are analysed. First, instead of using the mean value of 138 kWh energy per kWh LIB, the effect of using the lower given value of 97 kWh energy per kWh LIB is modelled in S1_LIB_low. The calculated default supply chain emissions without LIB indicated in Table 39 are, for this reason, correlated with the respective LIB production emissions based on Romare and Dahllöf (2017). Figure 67 shows a noticeable effect on supply chain emissions especially in 2025 and 2030 when average electricity mixes are more CO_2-intensive than in 2050. Assuming the lower electricity demand, S1_LIB_low results in a carbon budget overshoot of 32%, i.e. 2% lower than in S1. Second, the effect of using the upper given value of 181 kWh energy per kWh LIB is modelled in S1_LIB_high. Again, the effect of relative supply chain emissions is most pronounced in 2025 and 2030 (Figure 68). The carbon budget overshoot is increased by one percentage point to 35%.

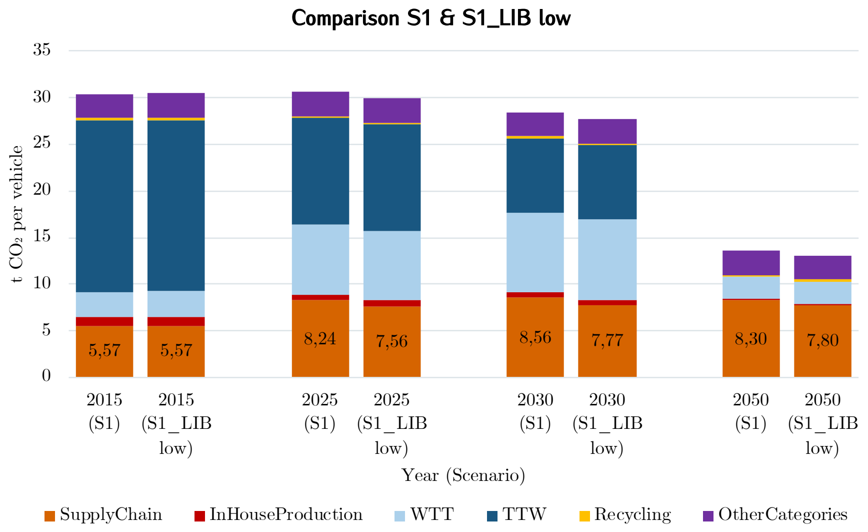


Figure 67 S1 versus S1_LIB_low: comparison of Group CO_2 emissions per average vehicle with mean electricity demand in LIB production (S1) and lower boundary electricity demand (S1_LIB_low).

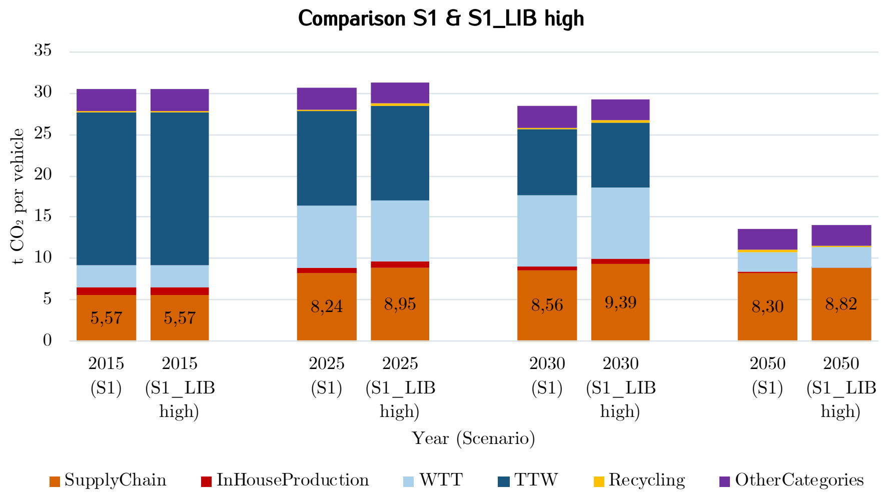


Figure 68 S1 versus S1_LIB_high: comparison of Group CO_2 emissions per average vehicle with mean electricity demand in LIB production (S1) and upper boundary electricity demand (S1_LIB_high).

This three percent insecurity corridor of budget overshoot in the modelled 35 year timespan shows that varying assumption on energy demand in LIB production have an impact on the Group's possibilities to comply with the carbon budget. However, when computing S1_LIB_high as well as S1_LIB_low with wind energy (Table 44), the carbon budget is each overshot by 28%. This resembles the overshoot in S2a in which the default LIB production energy requirement is assumed. After the finalisation of this exemplary modelling exercise, the Romare and Dahllöf (2017) study was updated. Emilsson and Dahllöf (2019) now use Dai and Winjobi (2019) as main source quoting a lower energy demand for cell production and battery pack assembly than before. Instead of the 350-650 MJ/kWh in Romare and Dahllöf (2017), only 216.2 MJ/kWh are indicated by Emilsson and Dahllöf (2019). When this energy lower energy demand is used as input parameter, it modifies the budget overshoot by only 0.6% compared to S1_LIB_low, i.e. still a rounded 30% budget overshoot is computed. Lowering electricity consumption during LIB production is thus overall important when renewable energy sources are not available.

5.4.2 Mobility demand & rebound effects

As shown in 3.4.4, models projecting future mobility demand and respective road transport emissions are highly complex. Still, different sources forecast coherent trends (see 2.3.1): (1) overall mobility demand is increasing, (2) the highest increase is expected in Asia, (3) EU and US mobility demands will develop similarly. As the amount of produced vehicles was shown to be positively correlated with the amount of absolute reported past emissions (see 2.2) as well as in the modelled scenario group 3, the effect of higher and lower mobility demands is analysed in the following. Due to constraints in data availability, possible rebound effects of wide-spread use of mobility services are not included in this analysis (see 5.1.7). Still, modelling the effect of higher mobility demand on Group absolute emissions in a scenario that includes mobility services is a rough estimation of the rebound effect's impact. An arbitrary deviation corridor of 10% higher and lower mobility demand is set for the years 2030 and 2050 based on the default input data sourced from OECD/ITF (2017). 2025 mobility demands are linearly interpolated. As can be seen in Table 58, if default mobility demands are lowered by 10% a shrinking market between 2015 and 2030 is the result in the US and EU.

Table 58 Modified mobility demand input parameters based on OECD/ITF (2017) and adapted by the indicated +/-10%.

Region	Year	Urban private mobility demand [billion p-km] +10%	Change in demand [%] 2015 -	Urban private mobility demand [billion p-km] -10%	Change in demand [%] 2015 -
OECD (EU, US in scenario analysis)	2015	8,953	-	8,953	-
	2025	-	14	-	-0.3
	2030	10,891	22	8,911	-0.5
	2050	13,127	47	10,740	20
Non-OECD (CN in scenario analysis)	2015	7,467	-	7,467	-
	2025	-	56	-	33
	2030	13,708	84	11,216	50
	2050	21,091	182	17,257	131

Higher mobility demand & rebound effects

If S1 is modelled with 10% higher mobility demands as shown in the above table, the Group's carbon budget is overshot by 38%. I.e. if a mobility demand 10% higher than projected is served by VW Group's vehicles, the 2015-2050 carbon budget is overshot by four percentage points more than in the default scenario. The 2 °C carbon budget was not underscored in any of the initial scenarios (including those focusing on mobility services). Therefore, a rebound effect of increased mobility demand can only raise the budget overshoot. If S4 is modelled with a 10% higher mobility demand, i.e. an assumed rebound effect, the carbon budget is overshot by 13%. The same increase in mobility demand in S1 and S4 results in an additionally higher budget overshoot for S4 (seven percentage points increase vs. four percentage points). The reason is that additional ride pooling vehicles in S4 cause higher life-cycle carbon emissions than additional average VW Group private vehicles. The necessity of pursuing CO_2-reduction measures over the life cycle of vehicles to attain absolute CO_2-reduction targets is thus accentuated when mobility demand (i.e. demand for vehicles) is higher than expected.

Lower mobility demand
If, in turn, S1 is modelled with 10% lower mobility demand than predicted, the VW Group's carbon budget is overshot by 28%, i.e. six percentage points less than in the default scenario. Although EU and US mobility demands are decreasing until 2030 in this sensitivity analysis, the uniformly projected immense increase of mobility demand in CN, resp. non-OECD countries, will increase total vehicle sales of OEMs active in these regions. A 10% lower mobility demand coupled with S4 "Mobility services & reduction measures" results in a 2% underscore of the budget (Figure 69). Likewise, S3b* (Ride hailing & Reduction measures) and S3c* (Ride pooling & reduction measures) coupled with a 10% lower mobility demand result in a 3% and 1% underscore, respectively.

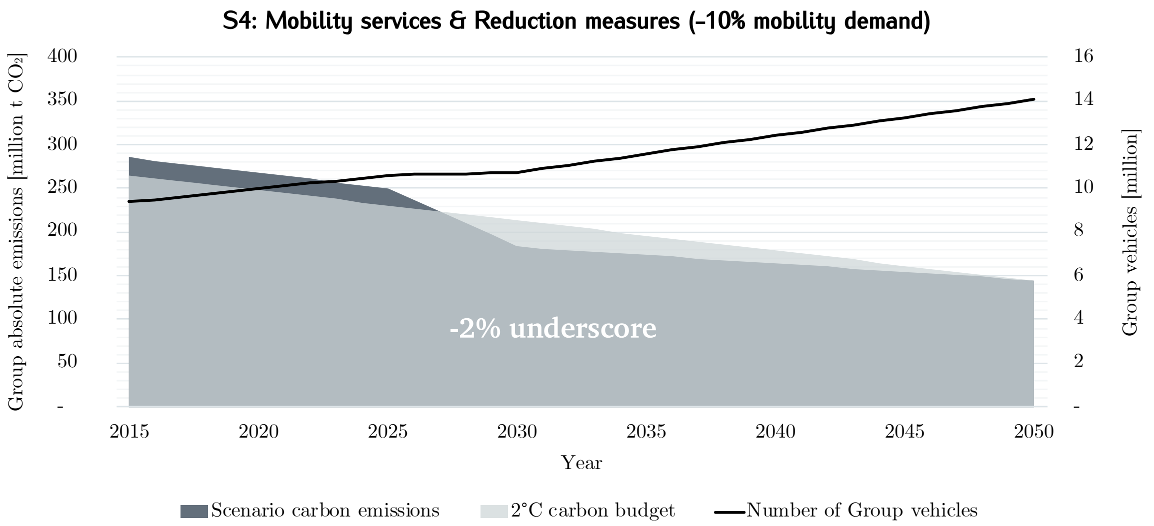


Figure 69 S4 Group absolute emissions with a continuously 10% lower mobility demand than projected (see Table 58).

5.4.3 Ride pooling load factor

Introducing ride pooling vehicles in OEMs' fleets is the most promising option of lowering the number of vehicles produced and used to serve the same mobility demand as with private vehicles. Higher assumed average load factors than car sharing and ride hailing result in the highest vehicle reduction potential in the scenarios modelled. As shown in S3c (5.3.8), the general carbon-reduction potential of producing and using fewer vehicles when engaging in ride pooling services is counterbalanced by higher life-cycle CO_2 emissions of the large BEVs used in the service even when the two assessed reduction measures are implemented. The crucial assumption in the ride pooling scenarios is the assumed load factor of 2.3 persons per v-km which determines the amount of ride pooling vehicles needed per year. To test the effect of a higher average load factor of ride pooling vehicles, the highest average load factor of 3 persons per v-km computed as being possible by Santi et al. (2014) is modelled for S3c.

With such a load factor, 9.4 million vehicles would have to be produced less between 2030 and 2050. The respective carbon budget overshoot in this scenario is 27% between 2015 and 2050, i.e. compared to the default setting in S3c the overshoot is lowered by five percentage points. If a ride pooling load factor of 3 is combined with S3c*, i.e. in combination with the reduction measures, the carbon budget is overshot by 2%. Hence, aiming for a higher capacity utilisation of mobility services and, as such, further reducing the number of needed vehicles is a crucial activity to be pursued by OEMs regarding carbon budget compliance.

5.5 Summary of method application

The chapter on method application is structured in four sections. Scenario development, model calibration and results are summarised in this part. Findings of the sensitivity analysis are incorporated in the discussion section below (6.5).

First, the scenarios which are to be modelled by applying the CBC method were developed according to the process specified in 4.12. Goal and scope applicable to all scenarios were described by referring to sub-research question 5 and justified by providing a list of influencing factors. It was highlighted that the scenarios do not aim at forecasting VW Group's absolute carbon emissions specifically but rather aim at testing the applicability of the CBC method by the example of the VW Group and within the set assumptions. The scenario landscape was presented including nine scenarios in total. Based on S1, the BAU scenario, both scenario group 2 focusing on reduction measures and scenario group 3 focusing on mobility services were derived. A concluding scenario merges assumptions of S2 and S3. Next, scenarios were classified based on the three macro characteristics a) goals, (b) design and (c) content of scenarios. Default settings, i.e. data inputs applicable to all scenarios if not stated otherwise were provided structured along twelve assumptions. Only 2015 input data used to specifically re-model the scenarios' starting year's absolute emissions was sourced from VW specific sources such as the annual and sustainability reports. Data inputs used to model future emissions were sourced from non-VW Group sources, i.e. generic information was correlated with VW-specific data. Finally, single storylines for each of the nine scenarios were provided including data inputs and assumptions diverting from the default settings.

In the second section, the model derived from the CBC method was calibrated with VW-specific past emissions data for 2015 and 2016. For both years, VW Group's absolute emissions were modelled with a deviation of -14%. Reasons for this underestimation were that modelled supply chain and WTW emissions are lower than the respective reported figures. As only six European reference LCA studies were used to model the global VW Group fleet, probably larger vehicles sold in the US and CN markets were not considered. Likewise, the reference vehicles TTW emissions are based on EU test cycles and did not include less strict TTW emissions legislations nor different test cycles in US and CN markets. In preparation of the following scenario analyses, the 2 °C-compatible carbon budget was calculated based on SBTi's absolute-based approach. In a first step, 2010 VW Group emissions were extrapolated as reporting started only 2012. Secondly, the carbon budget was lowered by 14% to be aligned with the VW total emissions modelled within the CBC method. The 2 °C-compatible carbon budget for VW Group between 2015 and 2050 thus amounted to 7.4 billion t CO_2.

In the third section, the modelling results were presented. In none of the main nor the additional scenarios were VW Group emissions complying with the 2 °C-compatible carbon budget (Table 59). In the BAU scenario in which reduction measures and mobility services are not included, the budget was overshot by 34%. Main reasons were the increasing mobility demand, especially in CN, and the assumed onset of the global fleet's electrification in 2025. While CO_2-intensities of average electricity mixes are still comparatively high, the fleet's increasing electrification leads to decreasing TTW emissions, on the one hand, but to increasing WTT and supply chain emissions, on the other hand. Furthermore, the differing impacts vehicle sales have in the three modelled markets on absolute emissions were analysed. Relative carbon emissions per average Group vehicle were highest in China due to the highest modelled CO_2-intensity of the electricity mix. With highest increases of mobility demand in China, emissions caused due to vehicles sold in China made up 56% of absolute VW Groupe emissions by 2050. In scenario group 2 these carbon hotspots were approached by modelling the use of wind energy as exemplary renewable energy source in electrified vehicles' use phase and LIB production. The combination of these measures resulted in a budget overshoot of 14%. Emission reductions caused by gradually decarbonising energy mixes for other components and production processes were not included in this conservative modelling exercise. The analysis of mobility services' impact on the VW Group's absolute emissions revealed differences in CO_2-reduction potentials between the three assessed services. Due to the assumed corresponding load factor of private and car sharing vehicles, in S3a the number of vehicles produced and used remained unchanged to S1. Only due to on earlier onset of the fleet's heavy electrification was the carbon budget overshoot lowered by two percentage points to 32%. The effect of only offering ride hailing to serve demand for mobility services was slightly higher. The budget was overshot by 30% mainly because the vehicle demand was moderately reduced and because ride hailing vehicles were assumed to be regular-sized vehicles only, i.e. vehicles with lower LIB capacities and electricity consumption. In S3c, the effect on VW Group emissions of only offering ride pooling vehicles was modelled. Although, compared to the other mobility services, the lowest number of vehicles was used to serve projected mobility demands, the carbon budget was still modelled to be overshot by 32%. The higher share of large BEVs increased both supply chain and WTT emissions to a degree that the carbon-saving effect of fewer vehicles was nearly fully counterbalanced. An overview of vehicle demands in S1, S3, S3b and S3c is depicted below.

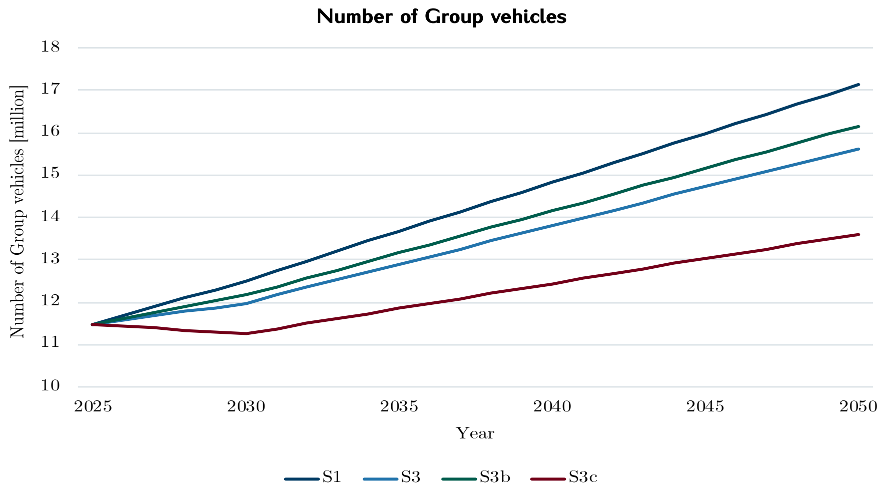


Figure 70 Overview of numbers of modelled Group vehicles in scenarios 1 (private vehicles), 3 (private vehicles, combination of mobility services), 3b (private vehicles, ride hailing), 3c (private vehicles, ride pooling).

In S4, the combined effect of applying wind energy in LIB production and during PHEV and BEV use phase on a Group fleet's composition and size shaped by all three mobility services is modelled. The resulting 6% overshoot of the carbon budget shows that only a combination of serving the growing mobility demand with a combination of private vehicles and services and the operationalization of high-leverage reduction measures opens up the possibility of overshooting the 2 °C-compatible carbon budget by less than 10%.

In order to compute whether VW Group can comply with their carbon budget given the chosen reduction measures, two additional scenarios were modelled. Following the finding that vehicle reduction via mobility service integration, life-cycle reduction measures, and the size of vehicles matter to diminish absolute emissions, both the ride hailing (S3b) and ride pooling scenario (S3c) are modelled with the discussed reduction measures. In these scenarios the budget is overshot by 5% and 6%, respectively. In order to provide an overview of modelled carbon budget overshoots, the results of the main and additional scenarios are summarised in Table 59.

Table 59 Summary of modelled carbon budget overshoot and underscore of main and additional scenarios.

Scenario		**Carbon budget overshoot or underscore [%]**
Main	S1: Business-as-usual	+34
	S2: Reduction measures	+14
	S2a: Green LIB production	+28
	S2b: Green electrified use phase	+22
	S3: Mobility services	+31
	S3a: Car sharing	+32
	S3b: Ride hailing	+30
	S3c: Ride pooling	+32
	S4: Mobility services & reduction measures	+6
Additional	S3b*: Ride hailing & reduction measures	+5
	S3c*: Ride pooling & reduction measures	+7

6 Discussion

This section discusses whether the sub-research questions have been answered and the problem situation sufficiently addressed. The discussion is structured following the sub-research questions developed in section 1.3. Final conclusions regarding the main research question are drawn in chapter 7.

6.1 OEMs' current carbon management approaches

In order to answer sub-research question 1 ("What are existing carbon management approaches of OEMs?"), carbon management approaches used by OEMs were assessed. Currently, OEMs focus on past emissions carbon accounting which is well-documented and structured along the requirements of GHG Protocol (WBCSD and WRI, 2004). Both direct and indirect emissions (scopes 1-3) are annually published on the online platform of CDP (CDP, 2018a).

Data sources for carbon accounting used by different OEMs overlap. Vehicle LCA studies are the basis for calculating supply chain and recycling emissions. Market-specific reported fleet emissions averages and fixed lifetime vehicle kilometrages are used to estimate absolute use phase emissions. EMS provide data for calculating direct and indirect emissions caused by OEMs' production plants. Generic sources are used to compute less CO_2-intensive categories such as employee commuting (see 2.2).

An OEM-specific methodology aiming at modelling future emissions and deriving most efficient carbon reduction measures on company level is, however, non-existent. Researchers of the field itself point to missing practical approaches (Qian et al., 2018). The derived recommendation for the development of sector-specific future-oriented carbon management approaches is to base future emission modelling on past reported emissions (i.e. scopes 1-3) and data sources (Burritt et al., 2011; Murthy and Parisi, 2013). Methods to determine required levels of emissions reductions to stay within a 2 °C-compatible carbon budget are available. The SBTi provides approaches to calculate Paris Agreement-compatible reduction targets for OEMs (SBTi, 2018b). However, a method to model future absolute emissions and provide decision-support on how to achieve an absolute CO_2 reduction target is currently missing as the analysis of OEMs' existing carbon management approaches has shown.

6.2 OEMs' emission drivers

Internal and external drivers of OEMs' future absolute emissions were analysed to address sub-research question 2 ("Which factors influence future absolute emissions of OEMs?"). To the author's knowledge, this is the first time this question has been addressed.

It was shown above that a crucial internal factor influencing OEMs' absolute emissions are the product portfolios of different brands owned by the company. Brands can differ significantly in types of vehicles offered. Premium brands produce and sell larger vehicles with higher motorisation rates and extensive equipment components which, compared to smaller vehicles, have a higher life-cycle carbon footprint see e.g. Daimler (2018e) & (2018b). Therefore, product specifications at the vehicle level as well as the overall OEMs' fleet composition of vehicles with higher and lower carbon footprints as a result of brands' product portfolios matter. Although direct emissions from production sites make up only ca. 4% (Table 4) of absolute reported emissions of OEMs, the choice of energy sources and efforts to cut energy requirements have an impact on current and future absolute emissions. For this reason, OEMs are re-modelling their own power stations to become more CO_2-efficient (see e.g. dpa, 2018).

Main external factors are tightening tailpipe emission legislations and the resulting dependence of OEMs on the energy sector's decarbonisation efforts. OEMs can achieve stricter fleet emission averages only by shifting from offering ICEs to offering electrified vehicles like PHEVs and BEVs. The life-cycle approach of accounting carbon emissions as defined in the GHG Protocol puts the focus on using renewable energy sources for electrified vehicles' energy-intensive life-cycle phases. Only when using renewable electricity sources (like wind energy) for manufacturing of LIB and charging of vehicles, an electrified vehicles' life-cycle CO_2-performance is considerably better than that of an ICE (Helms et al., 2016). Closed loop recycling of LIB materials offers carbon reduction potential once considerable amounts of discarded batteries are available (Zheng et al., 2018). Likewise, future developments of enhanced battery technologies like solid state batteries might lower the battery carbon footprint compared to today's battery models (NMC, LFP, NCA) (Romare and Dahllöf, 2017).

It was shown that the more vehicles are produced and sold, the higher the OEMs' absolute emissions (see 2.2). Therefore, amount and type of future mobility demand will determine the effort OEMs must make to achieve absolute reduction targets. In particular, the projected rising mobility demand in non-OECD countries (OECD/ITF, 2017) will put pressure on OEMs to reduce carbon emissions per vehicle in order to reach absolute carbon reduction targets. However, this projected increasing mobility demand will not be met with private vehicles only.

Mobility services

The findings of this study's analysis indicate that demand for mobility services is predicted to increase mainly fuelled by the development of autonomous and cloud-based connected vehicles (PwC, 2017). OEMs are already offering mobility services like car sharing, ride hailing and ride pooling next to their conventional business of selling vehicles for customers' private use (Firnkorn and Shaheen, 2016; Neef et al., 2019). Mobility services are distinguished from private vehicles by their ownership: while private vehicles are owned by the customer, service vehicles remain property of the provider. Furthermore, services like ride hailing and ride pooling have higher load factors than private vehicles. On average, more passengers per vehicle-km are transported so that a higher number of person-km is provided per vehicle. Consequently, fewer vehicles are needed to serve a set mobility demand. Car sharing vehicles' load factor is similar to that of private vehicles (see Table 47 and Nijland and van Meerkerk (2017)). Still, as a customer or city planner, using car sharing is perceived as a more climate-friendly concept compared to owning a private vehicle. This is due to the active vehicle stock being lowered if rising shares of car sharing vehicles satisfy the mobility demand; i.e. fewer vehicles are seen on the streets at a certain point in time because there is less parking space occupied by temporarily unused private vehicles. This perspective is also depicted in estimations of replacement ratios of service and private vehicles. Mainly based on surveys among car sharing programs' members, the share of people who would replace or have replaced their private vehicle by using the service vehicles only has been calculated (Baptista et al., 2014; UBA, 2017).

However, a smaller active vehicle stock does not necessarily lead to lower production volumes (PwC, 2018) and, consequently, to lower absolute CO_2 emissions caused by the automotive manufacturers. This is especially true if the service vehicles' load factor is the same as that of private vehicles. Because the capacity utilisation of service vehicles is higher than that of private vehicles, their lifetime kilometrage is achieved in a shorter time span. Consequently, fleets are renewed faster so that new vehicles have to be produced. Hence, the focus on potential replacement ratios does not include the OEM perspective.

As for services with higher load factors like ride hailing and pooling fewer vehicles would be used and produced to serve a set amount of person-km (that is: mobility demand). Nonetheless, this study evaluated that if and in how far hybrid fleets of private vehicles and mobility services will result in a decrease of OEMs' future absolute emissions has not yet been assessed.

Yet unknown is also whether and how a widespread and affordable introduction of mobility services will alter individual mobility behaviour. Will the use of mobility services by elderly and kids boost future mobility demand and thus vehicle demand? Will mobility service customers use more public transport and go by bike compared to when they owned a vehicle? Or will they refrain from public transport and use mobility services even more? And, are there differences in changing mobility patterns in different markets? Finding valid causal relationships between mobility services and their effect on mobility demand is challenging, though (Firnkorn and Shaheen, 2016).

The necessity to provide answers to these questions goes beyond OEMs' carbon emissions modelling. Policy-makers must know which incentives are needed at what point in time to prevent climate-damaging rebound effects associated with mobility services from happening. Future research should thus address how the predicted increase of mobility service usage can be coupled with an increased usage of more climate-friendly transport modes like bikes and trains. In a next step, it should be analysed how these locally- and temporally-specific findings can be extrapolated to macro-scale and long-term models like the CBC method.

6.3 Mobility services in LCA

In order to address the delineated research gap of how the inclusion of mobility services in OEMs' fleets will impact their absolute emissions, the additional sub-research question 2a ("What are common characteristics of LCA-based approaches to assess and compare CO_2 performances of private and mobility service vehicles?") was developed. It was shown that vehicle LCA studies are a crucial data source for OEMs' carbon reporting (see above). Therefore, it was necessary to analyse how differences in lifetime, load factors and possible rebound effects among service and private vehicles are handled in the LCA method.

This study's findings indicate that life-cycle carbon performances can best be compared when using 'person-km' as a reference unit. As such, different load factors are considered for different modes of transport. Empty travels were identified as a decisive factor diminishing the total person-kilometrage offered by ride hailing and pooling vehicles (Fagnant and Kockelman, 2014). The amount of vehicle-km not available for passenger transport due to vehicles' relocation to pick up customers must thus be included in the LCA-based comparison of private and service vehicles. The generally poor data quality or lack of data in the research field is met with scenario-building to show a range of future developments. Quantification of rebound effects caused by mobility services is deemed important (Briceno et al., 2005; Kjaer et al., 2016) though empirically-collected data is scarce.

6.4 Method development & derivation

Requirements for the development of the CBC method were derived based on the analysis of OEMs' carbon management approaches and future emission drivers as well as the literature review focussing on LCA studies comparing service and private vehicles. Like this, sub-research question 3 is addressed ("Which requirements does the method need to meet in order to represent a high degree of scientific quality as well as practical applicability?"). An overview of the developed requirements is provided in Table 60.

Table 60 Summary of requirements used for screening and evaluation of methods.

Methodological		Practical	
Requirement	**Explanation**	**Requirement**	**Explanation**
Future-orientation	Computing future emission pathways based on reported past emissions of sold vehicles.	Compatibility	Adopting the same data sources as in current carbon accounting approaches.
Scope 1-3	Covering scope 1-3 emissions according to GHG Protocol.	Comprehensibility	Ensuring that the method's processes are being understood by stakeholders.
Carbon budget	Relating an OEM's annual absolute CO_2 emissions to a predefined carbon budget until 2050.	Company structure	Computing absolute emissions of company entities separately.
Reduction measures	Extrapolating hotspot carbon reduction measures from vehicle to fleet level.		
Mobility services	Including projections on demand for car sharing, ride hailing and ride pooling by quantifying the impact on fleet sizes and powertrain composition.		

Specific evaluation parameters were developed for each requirement to assess methods outside the corporate carbon management field for their ability to achieve the research objective. In addition to methods facilitating company-level environmental impact assessment (O-LCA, OEF), modular LCA approaches and techno-economic macro road transport emissions models were analysed.

No single method met all eight requirements. In turn, not all requirements were fully met by the assessed methods (see Table 24). Only a combination and enhancements of the approaches' characteristics delivered the basis for the CBC method thus addressing sub-research question 4: "how can practical and methodological requirements be integrated in one modelling method?" Here, in line with Linton et al. (2015) several modelling approaches were combined to develop a new technique altogether. An in-depth overview of the origin of the CBC method's elements is provided in Figure 26.

The LCA-based approaches O-LCA and OEF scored highest in the overall requirement evaluation. The two methods are applicable for companies aiming at calculating their past environmental or carbon footprint according to the GHG Protocol. As such, both approaches take on an "LCA$^+$ perspective" by including the three standard life-cycle phases and other indirect emission categories (like commuting) which are typically not included in product LCA studies. The modular LCA approach added to i.a. the CBC method's ability to compute the effect of reduction measures on fleet level over time in a resource-efficient manner. The LCA method was thus evaluated as being the suitable main structural element of the CBC method as it is the linking constituent between the GHG protocol, the OEF, the O-LCA and the modular LCA. Additionally, the modular LCA approach and the O-LCA both fully met the requirement of *comprehensibility*. Therefore, both the derivation of the CBC method's mode of calculation and proposed application follow the life-cycle phases resp. the application requirements set out within LCA-based guidelines like the ILCD handbook (EC-JRC, 2010) (see 4).

Missing characteristics of the assessed approaches regarding the research objective were OEM-specificity, modularisation of carbon-hotspots below product-level, and scenario-building power for time-series. As mentioned before, these methodological gaps were filled by either combining existing approaches or by newly developing single elements. Here, the early conclusion is that without the development of the CBC method OEMs would not be able to holistically model their future absolute carbon emissions in relation to a carbon budget.

The O-LCA's and OEF's approach of calculating company-level *scope 1-3* emissions in an integrated way (EC-JRC, 2012; Martínez Blanco et al., 2015) are combined to mirror OEMs' past emissions accounting. Here, the OEF's the use phase calculation was modified to compute emissions market-specifically and to fulfil the *compatibility* requirement. *Future-orientation* was met by combining the O-LCA's cluster-LCA studies with the OEF's regionalised use phase assessment and a modularised LCA approach (Buxmann et al., 2009; Steubing et al., 2016). By the use of modules to change input parameters such as electricity mixes for crucial life-cycle phases (i.e. use phase) or components (i.e. LIB) and correlating them with market- and time-specific fleet compositions, the impact of over-time developing parameters as well as *reduction measure*s can be modelled. A fleet emissions calculator needed to be added, however, to check for market-, and time-specific legal compliance.

Within the CBC method, several years of absolute emissions are modelled to relate emissions performance to a given *carbon budget*. Based on a starting year's past emissions, the default data basis like cluster vehicle LCAs are correlated with time- and market-specific vehicle sales projections. These projections are analysed to be either sourced internally based on OEMs' own forecasts or externally from techno-economic models like IEA's MoMo (see Fulton et al., 2009). The approach by ICCT (2012) was adopted to choose modelling points (i.e. years) depending on data availability and quality and to linearly interpolate missing data. The group fleet emission averages are calculated to match these with future legislations based on cluster vehicles, tailpipe emissions, and respective time-, market-, and brand-specific fleet compositions. This modelling step was based on O-LCA's approach to calculate single brands' emissions separately (Martínez Blanco et al., 2015) thus meeting the *company structure* requirement. Specifically modelled years as well as interpolated annual emissions are finally summarised over the whole modelling timespan to enable contextualising them with a set carbon budget.

Including *mobility services* in modelling OEM's future fleet compositions required a new approach altogether (see Figure 25). Projections on mobility demand indicated in person-km can be sourced from techno-economic models (see ICCT (2012)). By using shares of forecasted demands for different mobility services and private vehicles the projected total demand of person-km is distributed among the modelled modes of transport. Mode-specific load factors then determine the fleet's size and composition needed to serve the expected mobility demand. Additionally, available lifetime vehicle-km of mobility services are adjusted for empty travels. See Figure 27-Figure 30 for an in-depth depiction of the CBC method's data flows.

The method derivation section mostly focuses on the clear description of modes of calculation and data flows by providing the necessary formulas and diagrams for the readers to program the CBC method themselves. Like this, the method can be applied within any suitable software program. The section focuses less on the method's application; only general steps for scenario analysis and sensitivity analysis are proposed (see 4.12). These specifications are put into practice within the case study analysed in chapter 5. Although the exemplary method application is overall meant to analyse whether the CBC method is meeting the research objective, a step-by-step description of the scenario development, preparation of data, model calibration, etc. is provided. By means of this detailed description of the case study, the CBC method's application is comprehensible. In the future, however, a handbook for the use of the CBC method could be developed. Here, the specific proceedings explained in the case study could be translated into general requirements for the method application similarly to the O-LCA handbook (Martínez Blanco et al., 2015).

6.5 Method application

Chapter 5 on applying the CBC method to the VW Group in a case study seeks to answer sub-research question 5: "Does the method application demonstrate its applicability to evaluate carbon reduction measures over the life cycle of vehicles and mobility services regarding the compliance with a 2 °C-compatible carbon budget of an OEM?".

Here, the term “applicability” refers to the CBC method’s ability to give indications for the most efficient carbon reduction measures based on OEMs’ existing carbon accounting and data flows while taking into account future fleet compositions and relating these to a set carbon budget. As such, the aim of using the method is to give OEM managers recommendations on which measures over the life cycle of vehicles should be pursued based on their carbon reduction leverage on fleet level. In the scenario analyses, only publicly available data was used to test the applicability of the CBC method. Still, past reported emissions of the VW Group were re-modelled for two consecutive years with a deviation of only 14%. This indicates that the developed calculation methodology is robust. Even with fairly poor quality of input parameters, OEMs’ dominant emission categories (WTW, supply chain) can be reproduced. With specific internal input data, OEMs are likely to obtain more accurate results. The applicability of the CBC method within this dissertation can thus only be judged based on the generic assumptions and data inputs used in the scenario analysis.

Validity of modelling results

The modelling results lead to clear recommendations on which reduction measures should be operationalised. It was shown that transferring high-leverage reduction measures at the vehicle level to fleet level is a valid approach to test their effect on an OEMs’ absolute emissions. The interplay of future fleet compositions and reduction measures is key to understand the validity of recommended courses of action derived from the modelling results.

Reduction measures

The measures *renewable energy sources in LIB production* and *PHEV/BEV use phase* were chosen to be modelled based on OEMs’ current strategy to electrify their fleets. If the strategy was to keep high shares of ICEs in the fleets, these reduction measures would not have shown a high reduction potential of absolute emissions. In this case, the most obvious reduction measure to be modelled on fleet level would have been a CO_2-efficient reduction measure on ICE vehicle level such as the use of renewable fuels. Due to the modular approach pursued in the CBC method, any fleet composition (including other powertrains such as FCEV) and any reduction over the life cycle of vehicles can be modelled if the necessary data is available. Based on the assumption of a steadily increasing future fleet electrification, the two modelled reduction measures were shown to be of major importance to increase the possibility of complying with the 2 °C-compatible carbon budget.

In all modelled scenarios, the operationalisation of using renewable energy throughout the life cycle of electrified vehicles is key to lower VW Group absolute emissions. The inclusion of the 2 °C-compatible carbon budget derived from the SBTi puts the leverage of reduction measures into perspective. In scenario 2, it was shown that operationalising both the included reduction measures leads to a major reduction in absolute emissions. Still, this reduction is not enough to comply with the carbon budget. The recommendation to use renewable energy in LIB production was verified for lower and upper boundary LIB production energy requirements. In other words, even with the lowest energy requirements, applying renewable energy sources is a priority reduction measure.

Due to data availability not every component and production process in the material supply chains could be coupled to market- and time-specific electricity mixes which are expected to gradually become less CO_2-intensive. Therefore, modelling results are based on the conservative assumption that e.g. steel and aluminium production emissions remain constant. If all upstream processes were connected to the respective forecasted energy mixes, computed absolute and relative emissions were lower than indicated in this modelling exercise.

As data can be disaggregated at the brand and market levels, the CBC method additionally facilitates prioritising which brand should implement a reduction measure in which market first to achieve the highest reduction in emissions. According to modelling results from scenario 1, renewable energy should most importantly be used in China as electricity mixes are the least CO_2-efficient and vehicle sales are expected to increase the most, compared to other markets. Moreover, due to its size and activity in

China, the brand VWP would achieve the highest reduction of VW Group absolute emissions if they operationalised the measures compared to other brands.

The results and sensitivity analysis show that both the reduction of vehicle demand due to ride pooling and a lower mobility demand than originally expected results in the same main challenge: carbon emission per vehicle must be reduced even further. After the LIB production and PHEV/BEV use phase are supplied with renewable energy, other emission hotspots come into focus. Especially in 2050, remaining emissions caused in the supply chain as well as in “scope 3 other categories” make up the bulk of carbon emissions. In order to ensure that VW Group complies with the 2 °C-compatible carbon budget in this scenario, other reduction measures in these categories should be evaluated. The modular approach pursued in the CBC method makes this possible.

For example, the impact of using steel with a reduced carbon footprint compared to conventional steel could be modelled as recently proposed in Germany (Wieschemeyer, 2019). ThyssenKrupp announced that its steel carbon footprint could be immediately reduced by 20-35% by applying novel production techniques (thyssenkrupp, 2019). Exchanging data between suppliers and automotive OEMs to model the reduction potential of specific measures and to infer needed amounts of carbon-reduced materials must therefore be a major activity to be pursued by OEMs in order to attain at least a 2 °C target. Future research should hence address how an efficient information exchange between suppliers and OEMs can bring mutual benefits in attaining carbon (or, in general, environmental) targets.

The same recommendation holds true to facilitate a close cooperation between OEMs and battery manufacturers. Battery technologies are evolving fast (Romare and Dahllöf, 2017) so that OEMs’ main interest should be to support battery manufacturers in developing energy-efficient modes of production next to increasing battery ranges. Additionally, OEMs can choose manufacturers using renewable energy sources and producing in favourable environments. For example, Emilsson and Dahllöf (2019) state that battery cell producers in cold and dry areas have a considerably lower energy consumption to dry the air in the dry room than in warmer and humid areas.

Scope 3 other categories

“Scope 3 other categories” are computed as a black box process with constant 2015 emission figures. The initial reasoning for disregarding these less CO_2-intensive categories was that many of these emission categories are not accounted for based on primary data but, rather, on generic data sources. Hence, deriving specific reduction measures is not possible at this point. The scenario analysis, however, showed that categories such as logistics and business travel gain significant importance for complying with the carbon budget once high-leverage reduction measures are operationalised. Therefore, improving the data basis and modes of calculation of these categories in past emissions accounting is necessary. Similar to reduction targets of in-house production emissions included in the scenarios, specific targets for the remaining scope 3 categories could thus be incorporated in the model.

Mobility services

Based on the modelling results of scenario 4 and scenarios 3b-c*, the recommendation to implement the two included reduction measures stays valid for OEMs introducing electrified mobility services in their fleets. Following the logic of scenario group 3, selling mobility services instead of private vehicles is not a choice taken by OEMs to reduce emissions but rather a changing demand by customers that is satisfied. Still, assessing the impact that different mobility services in OEMs’ fleets have on absolute emissions yields clear implications. Car sharing, ride hailing and pooling provide the possibility for an earlier onset of the fleet’s electrification. The accompanying recommended high-leverage reduction measures are the same as for private vehicles. Only a combination of reduction measures and reduced vehicle demand due to ride hailing and ride pooling lowers the 2 °C-compatible carbon budget overshoot to under 10%. In addition to the reduced number of vehicles, the type of mobility service facilitating the reduction matters. Though larger and heavier ride pooling vehicles transport more passengers thus reducing vehicle demand most, their supply chain emissions remain high even after implementing renewable energy in LIB production. In the sensitivity analysis, the influence of average load factors regarding carbon budget compliance was highlighted. Increasing the ride pooling load factor from the default 2.3 to 3 persons per v-km yields leads to a five percent lower budget overshoot due to a lower number of produced vehicles. The used 3 persons per v-km average load factor by Santi et al. (2014) is the highest computable ride pooling load factor found. OEMs offering mobility services should therefore focus on researching how constantly high load factors are achievable.

Although specific data on rebound effects induced by offering mobility services could not be obtained, including these effects in CBC method is possible. It is shown that projections on future mobility demand can be modified according to information on rebound effects. In the above analysis, an arbitrary 10% additional mobility demand is modelled. The respective increase in vehicle demand results in a higher budget overshoot. OEMs should thus pursue the scenario-approach applied in this study and model ranges of future mobility demands to account for potential rebound effects induced by mobility services.

Renewable energy sources

One major outcome from the scenario analysis is the high dependency of OEMs on CO_2-intensities of electricity mixes. The question whether enough renewable energy sources would be available to operationalise the modelled measures remains unanswered in this study. Still, the resulting recommendation for OEMs is to work closely together with energy providers to ensure that sufficient supplies of renewable energy is available. BMW, for example, sells solar panel installation in combination with their electric vehicles (BMW, 2018d). Consequently, the customers themselves provide for the needed low-carbon energy. VW Group already became an energy provider itself by founding the company Elli which invests in the production of renewable energy (VW, 2019f).

<u>Limitations</u>

Limitations of the discussed findings comprise methodological and data availability issues. In general, modelling results would be more precise if higher-quality data was available. Based on public data, only six reference model LCA studies were used to calculate life-cycle carbon emissions of different brands. Furthermore, CO_2 emission figures for the large BEV reference vehicle were inferred from the large PHEV reference vehicle as no specific study was available at the time of modelling.

LIB production

The carbon emissions caused by manufacturing the batteries of electrified vehicles were estimated based on indicated battery sizes and the generic emission factor provided in the review by Romare and Dahllöf (2017). The data quality could be improved by taking the specific data concerning battery production as used in the reference model LCA studies. As such, it can be ensured that the battery production module in the CBC method fits the primary assumption of the LCAs. As this information is not publicly available, here, a generic approach was used.

As battery production was shown to be a major emission driver resp. reduction lever, the battery module is worth improving. In the follow-up publication of Romare and Dahllöf (2017) by Emilsson and Dahllöf (2019) energy intensities of LIB production are further distinguished in electricity and natural gas requirements. Furthermore, the authors review which cell components are most energy-intensive (NMC111 powder and graphite). With a better data basis, the LIB module in the CBC method can be further refined to compute more precise and additional reduction measures and subsequently extrapolate these to fleet levels.

A higher amount of reference LCA studies and a refined LIB module could improve the validity of modelling results (i.e. lower the 7% deviation from the baseline 2015 Group supply chain emissions) and thus recommendations for OEM managers. Another limiting factor concerning LIB production emissions in the CBC method's application is future battery technologies. Trying to predict which LIB technologies will dominate a certain market in 30 years is like consulting a crystal ball. Still, once the data is available, scenarios including different battery technologies such as solid state batteries should be modelled. Consequently, choices concerning the battery technology could be supported not only by manufacturing price and range but also from a carbon life-cycle perspective. Due to the modular approach pursued in the CBC method, the inclusion of different battery technologies at different temporal or geographic scales is possible.

Supply chain and scope 3 other categories: data availability

Equally to LIB production processes, the remaining vehicle components' production processes are becoming more CO_2-efficient over time due to the forecasted decarbonisation of the energy sector until 2050. This holds also true for processes covered in scope 3 other categories such as waste treatment and logistics. However, this development is only specifically modelled for the two identified hotspots of LIB production and electrified vehicles' use phase. Due to data availability not every upstream and downstream process could be linked to a market and time-specific energy resp. electricity module. If all remaining processes were modelled specifically, the modelled carbon budget overshoot was lower than indicated. The conservative modelling approach pursued in this case study should be kept in mind when interpreting the results.

Availability of materials and renewable energy sources

As stated above, the availability of renewable electricity sources to satisfy the huge electricity demands caused by electrified fleets in the future is outside the scope of this study. Similarly, availabilities of rare earth elements (REEs) for the globally increasing electrified vehicle production were not assessed. However, the widespread deployment of such low-carbon technologies is only possible with a secure supply of adequate raw materials. Questions that remain to be addressed are (a) whether the REEs natural reserves for a specific technology will be sufficient at a certain point in time and (b) whether these REEs will be affordable if the global demand escalates. Currently, China is dominating global REE production (Barteková, 2015) which makes US and EU OEMs dependent on China (Charalampides et al., 2015). Therefore, the CBC method could be coupled to material flow analyses as presented by Fishman et al. (2018). The authors developed a model to assess the effects of deploying new technologies such as batteries in the automotive industry on material supply and demand. Additionally, it is possible to compute the extent to which discarded vehicles and their batteries will be able to absorb the growing material demands.

Both increasing demands for renewable electricity sources and REE could further be analysed from a consequential LCA point of view. As explained above (see 2.1), consequential modelling assesses whether decisions taken in a foreground system (e.g. OEMs' electrification strategy) affect the background system, for example, the REE and energy sector (EC-JRC, 2010). A research question such as "what are system-wide carbon emission consequences of large-scale substitution of renewable electricity sources for average electricity grid mixes in BEVs' and PHEVs' use phase in EU/USA/CN until 2050?" could be addressed. Palazzo and Geyer (2019) addressed a similar question for aluminium for steel substitution in the vehicle body in North America. The authors use system expansion to include the scrap and material markets in their analysis. Analogously, system expansion could be used to include the energy and REE markets in the analyses performed within the CBC method.

Carbon budget

The VW Group-specific carbon budget was calculated based on the absolute-based approach of the SBTi as no internal data could be sourced to use the recommended transport sector-specific SDA tool (SBTi, 2019c). It is probable that the respective resulting carbon budget from applying the SDA tool will differ from the absolute-based budget. An estimation of the budgets' deviation is, however, not possible with publicly-available data. The CBC method can be coupled with both approaches as only the computed emissions reduction pathway would have to be modified. Likewise, it is possible to adjust the underlying carbon budget due to target recalculation. The SBTi requires companies to revalidate their targets at least every five years to incorporate e.g. new emissions scenarios published by the IPCC (SBTi, 2019d).

Mobility services

Mobility demand forecasts used as input parameters to the CBC method are generic as only OECD and non-OECD countries are distinguished in the source used (see OECD/ITF, 2017). Consequently, differences in amount and type of mobility demand in different markets are disregarded. With internal data being available, OEM carbon practitioners can model emerging markets separately within the CBC method. Such regional specification will make further in-depth analyses possible. In this study, mobility developments in emerging markets, such as the African continent, are overlooked. What will be the effect on VW Group carbon emissions if new markets such as Rwanda are opened up not by selling vehicles but by offering mobility services only (VW, 2018c)? Such examples of possible "lifestyle leapfrogging", i.e. consumers in emerging economies adapting less resource-intense lifestyles than, for example, consumers in the EU (Schroeder and Anantharaman, 2017) should be included in analyses performed within the CBC method.

Whether so-called leapfrogging and the inclusion of mobility services in OEMs' fleets in general is actually diminishing OEMs' carbon emissions starts the discussion on the CBC method's methodological limitations. Similar to public data on projected mobility demands, forecasts on mobility service demand post-2030 could not be obtained. The shift from using a privately owned vehicle to using mobility services is not only accompanied by technological changes but foremost by behavioural ones. This study's findings indicate that rebound effects should be included in LCAs of Product-Service Systems (PSS) like mobility services and thus in OEMs' absolute emissions modelling. However, calculating such effects before the market-wide roll-out of the assessed PSS puts high demands on data quality which can mostly not be met (Kjaer et al., 2016). Therefore, quantifying these kinds of rebound effects is currently based on assumptions only (see e.g. Briceno et al., 2005). This data gap highlights the need for more empirical studies in the research field. Complex processes such as changing choices of transport modes need to be analysed further. Similarly, the interplay between different modes of transport like vehicles, bikes and trains is not assessed in this study.

Another important research topic is how average load factors of mobility services can be increased as this was shown to be a decisive factor in lowering vehicle demand. The realization of such a high load factor is not addressed in this study. It is vital, however, for OEMs to invest in researching this topic, both to reach climate targets and to increase revenues by offering the service. For this reason, micro-scale behavioural and agent-based models as presented by Linton et al. (2015) need to be correlated with macro-scale models. The CBC method is partly derived from macro-scale techno-economic models (see i.a. ICCT, 2012). Future research should focus on combining local or regional behavioural models with the CBC method. As a result, the effect of new policies on individual and region-specific choices of travel mode as shown by Hatzopoulou et al. (2011) could be included in modelling OEMs' future carbon emissions. Consequently, effective policies to support resource-efficient mobility from a societal perspective as well as from an OEM perspective could be derived. A corresponding follow-up research question is the extent to which mobility service demands differ between rural and urban areas and how mobility services can be effectively deployed in areas with lower population and thus, lower service vehicle densities. Likewise, Rodier and Podolsky (2017) call for more research on this topic.

Camacho Alcocer et al. (2018) bring the corresponding technological shift from private to service vehicles into focus. Corresponding to the ACES trend (see Figure 12) described by McKinsey&Company (2019) and PwC (2017), the authors highlight the potential of electrified autonomous service vehicles to satisfy mobility demand in rural areas. In this dissertation, technological differences between conventional and autonomous vehicles are neglected. Nonetheless, Gawron et al. (2018) determined that additional electronic equipment in connected and automated vehicles (CAVs) can increase life-cycle carbon emissions by 3-20% compared to conventional vehicles. As soon as OEMs have access to LCA studies of their mobility service CAVs, these studies should be included in the CBC method as a reference vehicle LCA for mobility services. As such, quantifying carbon reduction measures directed specifically at CAVs would be facilitated.

Practical applicability of the CBC method

The quality of modelling results could be further increased if instead of only four specifically modelled years every year was modelled specifically. Because of data on e.g. electricity mixes and mobility demand only being available for certain years, linear interpolation between modelling points is a feasible option for this public data analysis. Though this approach is in line with long-term road transport emissions models and scenario analyses' results clearly demonstrate which reduction measures should be implemented, it might not yet be suitable for OEMs' daily business operations.

As Krabbe et al. (2015) note in their publication on Paris Agreement-compatible target-setting, projections of long-term market growth are uncertain. For this reason, the authors recommend setting reduction targets for shorter timespans and re-evaluating their levels regularly. The CBC method could be used not only to model "the big picture", i.e. emission pathways until 2050, but also shorter timespans for which more reliable input data is available (e.g. for future fleet emission legislations). OEMs' fleet planning could be directly coupled with the CBC method. OEMs need to plan their future fleet size and composition to achieve tailpipe emissions compliance. Such compliantly planned fleet information could be used as input for modelling carbon budget compliance. As such, managers can be informed about absolute emissions caused by those specifically planned fleets.

The basic notion of the CBC method is its compatibility with existing past-oriented carbon accounting systems. Compatibility should be amplified with fleet planning programs in order to resource-efficiently analyse future fleets' impact on absolute emissions. The analysed impact of reduction measures in combination with planned fleets could then be used in the "Checking and corrective action" phase of the Carbon Management Circle (Figure 6). Thus, the progress towards a targeted emission level can be monitored and, if necessary, additional reduction measures implemented. To allow for this increased data processing, a tool with automated interfaces to supplying information systems could be developed. A KPI as recommended by Busch (2010) could be used to monitor emission reduction progress. Instead of only focusing on absolute emissions, life-cycle carbon emissions per average vehicle can be used as a KPI. Such a KPI is compatible with the CBC method as evaluating average vehicles' life cycle emissions is already part of the scenario analysis (see e.g. Figure 40). Establishing KPIs to monitor and control absolute carbon reduction targets is also recommended by the UN German Global Compact Network (2017).

Finally, OEM managers will not only base their decisions on prioritising measures on respective carbon reduction leverages but also on the operationalisation cost. This will become especially important when reduction measures demand high and long-term investment costs such as the retrofitting of steelworks to lower materials' carbon footprint (see e.g. thyssenkrupp (2019)). Harpankar (2019) states that global corporations with long-term investment cycles establish internal carbon pricing mechanisms to avoid future risks related to market-specific carbon regulations. Likewise, internal carbon pricing is used to achieve carbon reduction goals. The author differentiates between three models: carbon fees, shadow pricing and implicit pricing. In the carbon fee approach, a monetary value per unit of carbon emissions is added to a company's operational costs. These additional expenditures can be internally collected and re-invested in carbon reduction activities. The shadow pricing method is used to facilitate scenario analyses of varying future carbon prices. A forecasted price is integrated in investment plans to assess the impact of different prices on the company's return on investment. In the implicit pricing approach, the internal carbon price is based on the company's past spending in reduction measures and for legislation compliance. The price thus depends on the marginal abatement cost of carbon emission reduction (Harpankar, 2019). Future research should thus focus additionally on which type or combination of internal carbon pricing best fits OEMs' needs in accordance with the CBC method.

Although the budget is not underscored in any of the initially planned scenarios, the most effective reduction measures for electrified fleets are clearly indicated. Operationalising the use of renewable energy sources in electrified vehicles use phase as well as for LIB production is key. Additionally, high average load factors of mobility service vehicles are crucial to diminish the amount of needed vehicles to provide a given mobility demand.

In order to model scenarios resulting in carbon budget compliance without modifying projected mobility demands, additional reduction measures need to be extrapolated from vehicle to fleet level. The results clearly indicate that modelling the effect of additional reduction measures in the supply chains and in "scope 3 other categories" should be prioritized. These recommendations show that *sub-research question 5* can be positively answered. The CBC method thus demonstrated its applicability to evaluate the leverage of reduction measures and the introduction of mobility services regarding the compliance with a 2 °C-compatible carbon budget.

7 Conclusion

This dissertation aimed to address how existing carbon management approaches of automotive OEMs can be enabled to model future absolute emissions at the company level to facilitate compliance with a carbon budget. The introductory analysis of the state of current academic knowledge proves the validity and necessity of this overarching research question. So far, OEMs are applying past-oriented carbon accounting approaches to annually report their scope 1-3 emissions according to the GHG protocol. As LDV sales are globally increasing, OEMs' carbon emissions arising over the life cycle of produced vehicles are likewise increasing. Automotive OEMs are thus facing the challenge to reduce absolute carbon emissions while mobility demand is expected to rise further - a demand for both private vehicles and mobility services. The organisation SBTi provides approaches to calculate company-specific carbon reduction targets in line with the requirements to keeping global warming below 2 °C. Hence, the information on how much emissions must be reduced to avoid a climate catastrophe is available. The approach on how to (most effectively) reduce life-cycle carbon emissions at the company level to attain such a target is not. This delineates the research gap addressed in this dissertation: the development of the Carbon Budget Compliance (CBC) method.

To enable existing past-oriented carbon management approaches to model future emissions in relation to a carbon budget, both methodological and practical requirements must be met. These requirements are derived from the analysis of OEMs' future emissions drivers as well as the corporate carbon management literature. To ensure the CBC method's applicability by OEMs, it needs to be compatible with current carbon accounting approaches. These mainly rely on extrapolating supply chain and recycling emissions of vehicle LCA studies and reported use phase emissions averages to fleet levels. Applicability is further assured by comprehensibly documenting modes of calculation and by facilitating absolute emissions modelling of single entities separately. As such, OEMs' brands with different vehicle portfolios can derive specific carbon reduction strategies but are summarised on group level to ensure attaining targets as a whole. Methodological requirements address the method's future-orientation, i.e., the ability to model future scenario emissions based on past reported scope 1-3 emissions. Furthermore, these computed emissions must be related to a predefined carbon budget, thus pursuing a distance-to-target approach. In order to analyse how carbon emissions overshooting the budget can be reduced, the CBC method must facilitate calculating reduction measures at the vehicle level to subsequently extrapolate the impact to the fleet level. For this reason, it needs to be possible to compute emissions of single life-cycle phases or the manufacturing of vehicle parts outside of vehicle LCA studies used for carbon accounting. The final methodological requirement for the CBC method addresses mobility services being included in OEMs' fleets. As mobility services such as car sharing, ride hailing and ride pooling are not yet providing large shares of demanded person-km, their integration in OEMs' carbon emissions computing represents a complete novelty. From a life-cycle perspective, mobility service vehicles are distinguished from private vehicles in their use phases. As capacity utilisations and average load factors (of ride hailing and pooling vehicles) are higher than those of private vehicles, service vehicles' lifespans are shorter while provided total person-km are higher. Therefore, life-cycle emissions modelling of private and service vehicles fleets must use total person-km as reference unit instead of total vehicle-km. Consequently, future fleet sizes (and thus OEMs' emissions) can be computed based on vehicles' load factors.

None of the additionally assessed methods meets all requirements. The mobility service requirement was not met by any of the methodologies and thus highlighted the unprecedented perspective of the CBC method. O-LCA and OEF both serve as core approaches for the CBC method. These are amplified by a modular LCA approach to facilitate computing powertrain-specific reduction measures on fleet level. Techno-economic road transport emissions models' mode of calculating vehicle demand over time based on projected mobility demand and load factors is modified to compute the size of OEMs' private and mobility service vehicle fleets. Like this, scenario analyses of varying time- and market-specific mobility demands as well as the fleet powertrain compositions regarding OEMs' absolute carbon emissions and thus carbon budget compliance are facilitated.

The CBC method's application by the example of the VW Group proves its practical applicability. Although only publicly available datasets were used to compute global scope 1-3 emissions between 2015 and 2050, past reported data is re-modelled with a deviation of only 14%. Data gaps regarding future mobility demands and CO_2-intensities of electricity mixes are interpolated as well as extrapolated. The exemplary 2 °C-compatible carbon budget adjusted to the modelling timespan was calculated based on the absolute-based approach by the SBTi (SBTi, 2018b). A conservative modelling approach was pursued regarding CO_2-intensities of energy mixes in material supply chains and other scope 3 categories such as logistics and waste treatment. In contrast to electrified vehicles' use phase and LIB production, these processes were not coupled with gradually decarbonising energy mixes. Though, the carbon budget is not underscored in any of the originally planned scenarios, clear guidance for OEM managers to achieve compliance can be derived from the analyses. The validity of modelling results and thus the recommended modes of action below are proven in the sensitivity analysis.

Recommendations to comply with a 2 °C-compatible carbon budget

(1) Operationalise high-leverage reduction measures like renewable energy sources used for LIB production and electrified vehicles' use phase on fleet level for both private and mobility service vehicles immediately.
(2) Ensure that enough renewable energy is available to manufacture and charge the fleet.
(3) Aim for high load factors of mobility services to achieve most effective reductions of vehicle demand. Invest in research on how to achieve this goal.
(4) Consider the CO_2-intensity of large vehicles: if load factors of ride pooling vehicles are low, ride hailing vehicles facilitate a higher reduction of absolute emissions.
(5) Evaluate additional reduction measures in supply chain and "scope 3 other categories" on fleet level. Cooperate closely with suppliers to improve the data basis of emissions' calculation.

The confirmed practical applicability of the CBC method shows that the problem situation and research objective are sufficiently addressed and the main research question answered. By using the CBC method, OEMs are now capable to compute their future scope 1-3 emissions caused over the life cycle of private and service vehicles in relation to a given carbon budget. Reduction measures at the vehicle level can be extrapolated to fleet level to analyse their leverage to comply with the budget. Based on their impact, OEM managers can derive effective carbon reduction strategies to support achieving global climate targets.

Outlook

Future research should both address methodological and practical enhancements of the CBC method. Modelling the effect of mobility services on OEMs' fleet size is currently based on generic assumptions disregarding varying mobility demands between urban and rural areas and rebound effects. In order to derive more specific results, local or regional behavioural mobility models need to be combined with the CBC method. Consequently, the effects of policies on individual and region-specific choices of travel mode and thus vehicle demand could also be analysed. By automating data flows, scenario analysis within the CBC method could be more resource-efficient. OEMs need to plan future market-specific fleet sizes and powertrain compositions according to tailpipe emissions requirements. This data could be used as automated input for the CBC method. As such, life-cycle thinking can be directly incorporated in fleet planning. Future research should thus address what interfaces between existing data systems and the CBC method are beneficial for resource-efficient computing of future absolute emissions. Finally, the monetary aspect of operationalising reduction measures needs to be addressed. OEM managers will both take into account a measure's reduction lever at the company level as well as the price per reduced ton of CO_2. Future research should thus be focusing on how internal carbon pricing can be coupled with the CBC method.

8 Appendix

Table 61 2015 VWP shares of regular and large sized vehicles. Models according to VW (2016b), curb weights according to indicated sources.

VWP					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Golf	1095553	1245	R	18.6	(VW, 2019a)
Jetta	844907	1325	R	14.3	(VW, 2017e)
Polo	753754	1145	R	12.8	(VW, 2019g)
Passat	724018	1615	R	12.3	(VW, 2016c)
Tiguan	501712	1592	R	8.5	(VW, 2016d)
Lavida	462748	1325	R	7.8	(Wikipedia, 2019a)
Santana	279583	1210	R	4.7	(Wikipedia, 2018a)
Bora	202964	1345	R	3.4	(Wikipedia, 2019b)
Gol	192841	1055	R	3.3	(Wikipedia, 2018b)
Up!	172345	1380	R	2.0	(VW, 2019h)
Touran	120507	1505	R	1.8	(VW, 2019i)
Lamando	103574	1475	R	1.4	(Wikipedia, 2018c)
Fox	85161	1138	R	1.3	(Wikipedia, 2018d)
Saveiro	75397	1177	R	1.1	(Wikipedia, 2018e)
Beetle	64035	1340	R	1.0	(VW, 2017f)
Touareg	59190	2070	L	1.0	(VW, 2019j)
CC	56796	1707	L	<1	(Wikipedia, 2019c)
Sharan	53423	1767	L	<1	(VW, 2019k)
Suran	24691	1182	R	<1	(Wikipedia, 2018f)
Scirocco	16251	1280	R	<1	(VW, 2017g)
Eos	4559	1627	R	<1	(Wikipedia, 2019d)
Phaeton	2924	2598	L	<1	(Wikipedia, 2019e)
XL1	59	795	R	<1	(Wikipedia, 2019f)
Sum vehicles	5896991				
Share R;L	R= 97% (1303 kg average); L=3% (2036 kg average)				

Table 62 2015 AUDI shares of regular and large sized vehicles. Models according to VW (2016a), curb weights according to indicated sources.

AUDI					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
A3	370144	1320	R	20.3	(AUDI, 2008a)
A4	318788	1735	L	17.4	(AUDI, 2008b)
A6	293960	1975	L	16.1	(AUDI, 2016b)
Q5	267861	1850	L	14.7	(AUDI, 2014a)
Q3	205445	1535	R	11.2	(AUDI, 2019c)
A1	116250	1145	R	6.4	(AUDI, 2014b)
Q7	82340	2145	L	4.5	(AUDI, 2019a)
A5	79133	1715	L	4.3	(AUDI, 2015)
TT	35510	1260	R	1.9	(AUDI, 2006)
A7	29158	1925	L	1.6	(AUDI, 2016c)
A8	27065	1830	L	1.5	(AUDI, 2007)
R8	2074	1565	R	<1	(AUDI, 2009)
Q2	67	1300	R	<1	(AUDI, 2019d)
Sum vehicles	1827795				
Share R;L	R=40% (1354 kg average); L=60% (1882 kg average)				

Table 63 2015 ŠKODA shares of regular and large sized vehicles. Models according to VW (2016a), curb weights according to indicated sources.

ŠKODA					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Octavia	425629	1247	R	41.0	(SKODA, 2018a)
Fabia	195349	1199	R	18.8	(SKODA, 2018b)
Rapid	189187	1265	R	18.2	(SKODA, 2018c)
Yeti	89890	1585	R	8.7	(SKODA, 2015)
Superb	84550	1440	R	8.2	(SKODA, 2018d)
Citigo	41280	940	R	4.0	(SKODA, 2018e)
Roomster	11166	1250	R	1.1	(ADAC, 2009)
Sum vehicles	1037051				
Share R;L	R=100% (1,275 kg average) ; L=0%				

Table 64 2015 SEAT shares of regular and large sized vehicles. Models according to VW (2016a), curb weights according to indicated sources.

SEAT					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Leon	169455	1342	R	40.8	(SEAT, 2019a)
Ibiza	160451	1172	R	38.7	(SEAT, 2019b)
Altea/Toledo	32729	1190	R	7.9	(SEAT, 2018)
Alhambra	27925	1805	L	6.7	(SEAT, 2019c)
Mii	24516	940	R	5.9	(SEAT, 2019d)
Sum vehicles	415076				
Share R;L	R=93% (1,161 kg average); L=7% (1,805 kg average)				

Table 65 2015 PAG shares of regular and large sized vehicles. Models according to VW (2016a), curb weights according to indicated sources.

PAG					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Macan	86016	1880	L	36.7	(PAG, 2017a)
Cayenne	79700	2235	L	34.0	(PAG, 2017b)
911 Coupé/Cabriolet	31373	1670	R	13.4	(PAG, 2017c)
Boxster/Cayman	21978	1365	R	9.4	(PAG, 2016)
Panamera	15055	1935	L	6.4	(PAG, 2017d)
918 Spyder	375	1300	R	<1	(PAG, 2011)
Sum vehicles	234497				
Share R;L	R=23% (1,445 kg average); L=77% (2,017 kg average)				

Table 66 2015 VWN shares of regular and large sized vehicles. Models according to VW (2016a), curb weights according to indicated sources.

VWN					
Model	**Volume 2015**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Caravelle/ Multivan	96341	2105	L	23.5	(VWN, 2018a)
Transporter	82509	1979	L	20.1	(VWN, 2018b)
Amarok	81019	2095	L	19.8	(VWN, 2018c)
Caddy	76048	1576	R	18.5	(VWN, 2016a)
Caddy Kombi	74302	1576	R	18.1	(VWN, 2016a)
Sum vehicles	410219				
Share R;L	R=37% (1,576 kg average); L=63% (2060 kg average)				

Table 67 2016 VWP shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

VWP					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Golf	982,495	1245	R	16.2	(VW, 2019a)
Jetta/Sagitar	968,135	1325	R	15.9	(VW, 2017e)
Polo	784,388	1145	R	13.1	(VW, 2019g)
Passat/Magotan	711,878	1615	R	11.7	(VW, 2016c)
Tiguan	548,687	1592	R	9.0	(VW, 2016d)
Lavida	547,187	1325	R	9.0	(Wikipedia, 2019a)
Santana	312,177	1210	R	5.1	(Wikipedia, 2018a)
Bora	236,427	1345	R	3.9	(Wikipedia, 2019b)
Gol	160,130	1055	R	2.6	(Wikipedia, 2018b)
Up!	169,970	1380	R	2.8	(VW, 2019h)
Touran	162,248	1505	R	2.7	(VW, 2019i)
Lamando	146,285	1475	R	2.4	(Wikipedia, 2018c)
Fox	50,273	1138	R	<1	(Wikipedia, 2018d)
Saveiro	47,460	1177	R	<1	(Wikipedia, 2018e)
Beetle	61,940	1340	R	<1	(VW, 2017f)
Touareg	47,495	2070	L	<1	(VW, 2019j)
CC	44,091	1707	L	<1	(Wikipedia, 2019c)
Sharan	41,949	1767	L	<1	(VW, 2019k)
Suran	20,163	1182	R	<1	(Wikipedia, 2018f)
Scirocco	11,963	1280	R	<1	(VW, 2017g)
Phideon	5,131	2025	L	<1	(VW, 2019l)
Phaeton	452	2598	L	<1	(Wikipedia, 2019e)
Atlas/Teramont	386	2042	L	<1	(VW, 2019m)
Sum vehicles	6,073,310				
Share R;L	R= 98% (1314 kg average); L=2% (2035 kg average)				

Table 68 2016 AUDI shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

AUDI					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
A3	361,983	1320	R	19.1	(AUDI, 2008a)
A4	357,999	1735	L	18.8	(AUDI, 2008b)
A6	276,211	1975	L	14.5	(AUDI, 2016b)
Q5	297,750	1850	L	15.7	(AUDI, 2014a)
Q3	231,452	1535	R	12.2	(AUDI, 2019c)
A1	105,252	1145	R	5.5	(AUDI, 2014b)
Q7	103,344	2145	L	5.4	(AUDI, 2019a)
A5	65,117	1715	L	3.4	(AUDI, 2015)
TT	26,886	1260	R	1.4	(AUDI, 2006)
A7	26,308	1925	L	1.4	(AUDI, 2016c)
A8	24,179	1830	L	1.3	(AUDI, 2007)
R8	3,688	1565	R	<1.0	(AUDI, 2009)
Q2	19,419	1300	R	1.0	(AUDI, 2019d)
Sum vehicles	1,899,588				
Share R;L	R=39% (1354 kg average); L=61% (1882 kg average)				

Table 69 2016 ŠKODA shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

ŠKODA					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Octavia	445,514	1247	R	38.9	(SKODA, 2018a)
Fabia	195,349	1199	R	17.1	(SKODA, 2018b)
Rapid	216,603	1265	R	18.9	(SKODA, 2018c)
Yeti	95,417	1585	R	8.3	(SKODA, 2015)
Superb	148,880	1440	R	13.0	(SKODA, 2018d)
Citigo	41,247	940	R	3.6	(SKODA, 2018e)
Kodiaq	1,167	1995	L	0.1	(SKODA, 2019)
Sum vehicles	1,144,078				
Share R;L	R=99.9% (1279 kg average) ; L=0.1% (1995 kg average)				

Table 70 2016 SEAT shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

SEAT					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Leon	163,228	1342	R	39.1	(SEAT, 2019a)
Ibiza	149,988	1172	R	36.0	(SEAT, 2019b)
Ateca	35,833	1589	R	8.6	(SEAT, 2019e)
Alhambra	31,214	1805	L	7.5	(SEAT, 2019c)
Mii	18720	940	R	4.5	(SEAT, 2019d)
Altea/Toleda	18,029	1190	R	4.3	(SEAT, 2018)
Sum vehicles	417,012				
Share R;L	R=93% (1,246 kg average); L=7% (1,805 kg average)				

Table 71 2016 PAG shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

PAG					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Macan	97,177	1880	L	40.6	(PAG, 2017a)
Cayenne	71,693	2235	L	29.9	(PAG, 2017b)
911 Coupé/Cabriolet	31,648	1670	R	13.2	(PAG, 2017c)
Boxster/Cayman	24,884	1365	R	10.4	(PAG, 2016)
Panamera	14,218	1935	L	5.9	(PAG, 2017d)
Sum vehicles	239,618				
Share R;L	R=24% (1,518 kg average); L=76% (2,017 kg average)				

Table 72 2016 VWN shares of regular and large sized vehicles. Models according to VW (2017d), curb weights according to indicated sources.

VWN					
Model	**Volume 2016**	**Curb weight [kg]**	**R=regular, L=large**	**Share of brand fleet [%]**	**Source**
Caravelle/ Multivan	117,554	2105	L	27.9	(VWN, 2018a)
Transporter	81,932	1979	L	19.4	(VWN, 2018b)
Amarok	63,367	2095	L	15.0	(VWN, 2018c)
Caddy	71,757	1576	R	17.0	(VWN, 2016a)
Caddy Kombi	86,841	1576	R	20.6	(VWN, 2016a)
Crafter	596	3158	L	0.1	(VWN, 2016b)
Sum vehicles	422,047				
Share R;L	R=37% (1,576 kg average); L=63% (2060 kg average)				

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List of abbreviations

BAU	Business-As-Usual
BEV	Battery Electric Vehicle
BMW	Bayrische Motoren Werke AG
BTS	Bureau of Transportation Statistics
CAV	Connected Autonomous Vehicle
Cat.	Category
CBC	Carbon Budget Compliance
CDP	Carbon Disclosure Project
CMA	Carbon Management Accounting
CMS	Carbon Management System
CN	People's Republic of China
DIN	German Institute for Standardization
DJSI	Dow Jones Sustainability Index
EC	European Commission
EMA	Environmental Management Accounting
EMS	Environmental Management System
EoL	End-of-Life
EPD	Environmental Product Declaration
EU	European Union
FCEV	Fuel-Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HDV	Heavy-Duty Vehicle
HFCs	Hydrofluorocarbons
ICCT	International Council for Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IM	Information Module
ITF	International Transport Forum
JV	Joint Venture
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LFP	Lithium iron phosphate
LIB	Lithium-Ion Battery
MaaS	Mobility as a Service
MoMo	Mobility Model
MFA	Material Flow Analysis
NCA	Lithium nickel cobalt aluminium oxide
NEDC	New European Driving Cycle
NMC	Lithium manganese cobalt oxide
OEF	Organisation Environmental Footprint
OEM	Original Equipment Manufacturer
O-LCA	Organisational Life Cycle Assessment
PAG	Porsche AG
PEF	PEF
PFCs	Perfluorocarbons
PHEV	Plug-in Hybrid Electric Vehicle
PSS	Product Service System

PwC	Pricewaterhouse Coopers
PEF	Product Environmental Footprint
REE	Rare Earth Element
RTS	Reference Technology Scenario
SAV	Shared Autonomous Vehicles
SBT	Science Based Target
SBTi	Science Based Targets Initiative
SDA	Sectoral Decarbonisation Approach
SUV	Sport Utility Vehicle
TTW	Tank-To-Wheel
UBA	German Environmental Ministry
US	United States of America
VW	Volkswagen Group
VWN	Volkswagen Commercial Vehicles
VWP	Volkswagen brand
WBCSD	World Business Council for Sustainable Development
WLTC	Worldwide Harmonised Light-Duty Vehicles Test Cycles
WRI	World Resources Institute
WTT	Well-To-Tank
WTW	Well-To-Wheel
WWF	World Wide Fund for Nature
2DS	2 °C-scenario

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Mara Aline Neef wurde 1990 in Göttingen geboren. Nach dem Abitur arbeitete sie ein Jahr für eine regionale Zeitung in Ecuador. Motiviert durch ihr Interesse an gesellschaftlichen und umweltbezogenen Themen nahm sie ein Bachelor-Studium der Politikwissenschaften und Biologie an den Universitäten Bremen und Glasgow auf. Nach ihrer Bachelor-Abschlussarbeit zum Thema Bodenrevitalisierung an der Universität Ngaoundéré in Kamerun studierte sie im Masterstudiengang Agrar- und Umweltwissenschaften an den Universitäten Kopenhagen und Hohenheim. Hier setzte sie sich insbesondere mit der Methode der Ökobilanzierung auseinander. Klimaschutz gehört für sie zu den wichtigsten Themen unserer Zeit. Die Entwicklung einer Methode zur Ableitung von wissenschaftlich fundierten Dekarbonisierungsstrategien für die Automobilindustrie im Rahmen ihrer Dissertation war und ist ihr daher eine Herzensangelegenheit.

Zum Inhalt:

Automobilhersteller (OEMs) verursachen den Ausstoß erheblicher Mengen an CO_2-Emissionen über den Lebenszyklus ihrer Fahrzeuge. Um den Klimawandel zu stoppen, müssen alle Industriesektoren, einschließlich der OEMs, CO_2-Emissionen massiv senken. Es existiert jedoch bislang keine Methode, mit der zukünftige absolute Emissionen von OEMs modelliert und Reduktionsmaßnahmen bewertet werden können. In dieser Dissertation wird die Carbon Budget Compliance (CBC) Methode entwickelt, welche die Berechnung des Hebels von Reduktionsmaßnahmen auf Flottenebene über den Lebenszyklus von Privat- und Service-Fahrzeugen hinsichtlich der Einhaltung von OEM-spezifischen CO_2-Budgets ermöglicht. Die CBC Methode wird exemplarisch in einer Fallstudie auf die Volkswagen AG angewendet, in der die absoluten Emissionen von 2015 bis 2050 hinsichtlich der Einhaltung eines 2 °C-kompatiblen CO_2-Budgets modelliert werden. In Szenarioanalysen wird der Effekt zweier Reduktionsmaßnahmen berechnet: die Nutzung erneuerbarer Energiequellen für die Batterieproduktion und für die Nutzungsphase elektrifizierter Fahrzeuge. Die betrachteten Flotten bestehen sowohl aus Privat- als auch aus Service-Fahrzeugen (Car Sharing, Ride Hailing, Ride Pooling). Durch die Flottenelektrifizierung sind OEMs auf die Dekarbonisierung des Energiesektors angewiesen. Um absolute Reduktionsziele erreichen zu können, sollten OEMs aktiv daran arbeiten die Verfügbarkeit ausreichender Mengen erneuerbarer Energien sicherzustellen. Zusätzlich sollten weitere Maßnahmen insbesondere in den Lieferketten mit der CBC Methode bewertet werden. Durch den modularen Ansatz der Methode ist die Modellierung verschiedenster Maßnahmen möglich.

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