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Ecological Assessment of Scenarios for the Energy Supply of the German Transport Sector

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Abstract

In order to ensure that greenhouse gas (GHG) emissions are reduced in line with the goals of the Paris Agreement, emission reduction pathways must be found for the transport sector. To investigate possible emission reduction pathways, scenario studies are carried out, which are often limited to territorial borders. In contrast, the method of Life Cycle Assessment (LCA) is not bound by territorial borders and is used to evaluate all ecologically relevant impacts of a product or service, but neglects the systemic perspective. Therefore, this dissertation aims to integrate the LCA method into the modelling of the transport sector in the context of a dynamic energy system that aims to reach the goals of the Paris Agreement.

As a basis for assessing deep emission reduction scenarios, a bottom-up approach was used to map the German transport sector embedded in the European energy system. For the approach, a total of 157 different vehicle types and their energy consumption were modelled for passenger and freight transport in road, rail, inland waterway, and air transport. The derived energy demands were subsequently calculated to be provided in a cost-optimised manner by means of linear optimisation. Based on the energy supply, GHG emission factors were derived for two methods. The factors reflect the direct energy-related emissions on the one hand and the life cycle emissions on the other hand.

The two aspects of the integration of the life cycle perspective include the addition of upstream chain emissions for energy carriers and the integration of non-operational emissions from the production and end-of-life phase of the vehicles. The increase in operational emissions through the upstream chain in the current transport sector is found to be low at 14.3 % due to the high shares of fossil liquid hydrocarbons in the energy demand. When switching to a transport system with a high share of electrified vehicles, the increase due to the integration of the upstream chain was increased to 317.6 %. This value is significantly higher at 657.2 % for transport systems that predominantly rely on synthetic fuels. Non-operational emissions amount to 47.6 Mt CO_2e in 2020 and thus 19.2 % of total emissions in transport. The absolute non-operational emissions subsequently decrease in the scenarios. However, the decrease is found to be slower than in the operational emissions, and therefore their share grows.

The results have shown that the life cycle perspective is also essential in transport scenario assessments to avoid neglecting a large share of associated emissions. Especially for transport systems in which large shares of renewable electricity is directly and indirectly used, simple methods must be found to include indirect emissions.

Kurzfassung

Um sicherzustellen, dass die Treibhausgasemissionen in Übereinstimmung mit den Zielen des Pariser Abkommens reduziert werden, müssen entsprechende Reduktionspfade für den Verkehrssektor gefunden werden. Szenariostudien, die zur Untersuchung solcher Pfade durchgeführt werden, sind häufig auf territoriale Grenzen beschränkt. Dem gegenüber steht die Methode der Ökobilanz, die zwar alle ökologisch relevanten Auswirkungen eines Produkts oder einer Dienstleistung im In- und Ausland bewertet, jedoch systemische Effekte im Zuge einer zukünftigen Transition vernachlässigt. Ziel dieser Dissertation ist es daher, die Ökobilanz in die Modellierung des Verkehrssektors im Kontext eines dynamischen Energiesystems, das die Ziele des Pariser Abkommens erreichen soll, zu integrieren.

Als Grundlage für die Bewertung von Emissionsminderungsszenarien wurde ein Bottom-Up-Ansatz verwendet, um den deutschen Verkehrssektor, eingebettet in das europäische Energiesystem, abzubilden. Für den Ansatz wurden insgesamt 157 verschiedene Vehikeltypen samt ihres Energieverbrauchs für den Personen- und Güterverkehr auf Straße, Schiene, Wasser und in der Luft modelliert. Mithilfe linearer Optimierung wurde im Anschluss die Energiebereitstellung kostenoptimal ausgelegt. Darauf basierend wurden schließlich mittels zwei Methoden Emissionsfaktoren für die direkten Emissionen und die Lebenszyklusemissionen gebildet.

Im Zuge der Integration der Lebenszyklusperspektive wurden einerseits die Emissionen der Vorkette der Energieträger und andererseits nichtbetriebliche Emissionen aus der Produktion und dem Lebensende der Fahrzeuge ergänzt. Der Anstieg betrieblicher Emissionen durch die Vorkette im derzeitigen Verkehrssektor ist mit 14,3 % aufgrund des hohen Anteils fossiler flüssiger Kohlenwasserstoffe am Energiebedarf gering. Bei einer Umstellung auf hohe Anteile an elektrifizierten Fahrzeugen beträgt der Anstieg bis zu 317,6 % und bei Verkehrssystemen, die überwiegend synthetische Kraftstoffe verwenden bis zu 657,2 %. Die nichtbetrieblichen Emissionen belaufen sich im Jahr 2020 auf 47,6 Mt CO_2-Äq. und sind damit für 19,2 % der Gesamtemissionen des Verkehrs verantwortlich. Ähnlich wie die betrieblichen Emissionen nehmen sie im Verlauf der Szenarien ab. Dieser Rückgang verläuft jedoch langsamer als bei den betrieblichen Emissionen, so dass der Anteil von Produktion und Lebensende zunimmt.

Die Ergebnisse zeigen, dass auch bei der Bewertung von Verkehrsszenarien die Lebenszyklusperspektive von wesentlicher Bedeutung ist, da andernfalls ein großer Teil der mit dem Verkehr verbundenen Emissionen vernachlässigt wird. Insbesondere zur Bewertung von Verkehrssystemen, in denen große Teile direkt oder indirekt elektrifiziert werden, müssen einfache Methoden zur Einbeziehung indirekter Emissionen gefunden werden.

Contents

List of Abbreviations

ASTRA	Assessment of Transport Strategies
BEV	battery electric vehicle
CAPEX	capital expenditures
CCGT	combined cycle gas turbine
CHP	combined heat and power generation
CNG	compressed natural gas
COPERT	Computer Program to Calculate Emissions from Road Transport
DAC	Direct Air Capture
dena	German Energy Agency
DLR	German Aerospace Centre
DME	dimethyl ether
EEA	European Environment Agency
EMF	emission factor
EMPA	Swiss Federal Laboratories for Material Science and Technologies
EPA	Environmental Protection Agency
ETHZ	Eidgenössische Technische Hochschule Zürich
EU	European Union
EU ETS	EU Emission Trading System
FCEV	fuel cell electric vehicle
FF	FreeFloating
FT	Fischer-Tropsch

FT fuels	Fischer-Tropsch fuels
GDP	gross domestic product
GHG	Greenhouse Gas
GIS	geographic information system
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	global warming potential
GWP100	global warming potential over 100 years
HBEFA	Handbook of Road Transport Emission Factors
HDV	heavy duty vehicle
HEV	hybrid electric vehicle
HZH	Helmholtz Centre Hereon
IAM	Integrated Assessment Model
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IFEU	Institute for Energy and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
ISAaR	Integrated Simulation Model for Planning the Operation and Expansion of Power Plants with Regionalisation
KBA	Federal Motor Transport Authority
KD2045	Klimaneutrales Deutschland
KiD2010	Motor Vehicle Traffic in Germany 2010
KIT	Karlsruhe Institute of Technology
KN100	dena Leitstudie Aufbruch Klimaneutralität
KP	Klimapfade 2.0
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDV	light duty vehicle

LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MDV	mid duty vehicle
MiD2017	Mobility in Germany 2017
MInGa	Market and Infrastructure for Gas
MIT	motorised individual transport
MOVES	Motor Vehicle Emission Simulator
NDC	Nationally Determined Contribution
NIR	National Inventory Report
OCST	overhead catenary semi-trailer
OME	polyoxymethylene dimethyl ether
OPEX	operational expenditures
PEM	proton-exchange-membrane
PHEV	plug-in hybrid electric vehicle
pkm	passenger-kilometre
PM	particulate matter
premise	PRospective EnvironMental Impact AsSEssment
PSI	Paul Scherrer Institue
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
RCP	Representative Concentration Pathway
SB	station-based
SCCER	Swiss Competence Centre for Energy Research
SDA	System-Dynamic Assessment
SDLCA	System-Dynamic Life Cycle Assessment
SDP	Sustainable Development Goal

SMR	steam methane reforming
SSP	Shared Socioeconomic Pathway
SUV	sport utility vehicle
THELMA	Technology-centred Electric Mobility Assessment
tkm	tonne-kilometres
TraM	Transport Model
TREMOD	Transport Emission Model
UBA	German Environmental Agency
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
V2G	Vehicle-to-Grid
VAT	value-added tax
VEU	Traffic Development and Environment
VOC	volatile organic compounds
WLTP	Worldwide Harmonised Light Vehicles Test Procedure

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1 Introduction

This dissertation deals with scenario modelling and the Greenhouse Gas (GHG) emission assessment of the German transport sector. At the beginning of this introductory chapter, the motivation for the research on this topic is provided. Subsequently, the status quo of the modelling of transport and its emissions is presented before the objective of the thesis and the associated research questions are formulated.

1.1 Motivation

In February 2022, the Working Group II of the Intergovernmental Panel on Climate Change (IPCC) published their contribution to the Sixth Assessment report [1]. This report focuses on the interactions of the coupled systems of climate, ecosystems including biodiversity, and human society. It emphasises the impact of human-induced GHG emissions and also highlights the immense impact of climate on human society. Depending on the increase in global surface temperature, risks such as, among others, the risk of food security or malnutrition and loss of livelihood due to reduced food production from crops, livestock, and fisheries or increased human mortality and morbidity due to increased heat and infectious diseases threaten the human population. Carbon dioxide (CO_2) is the gas that makes up the largest contribution to GHG emissions [2]. Of the total 32.0 Gt of global CO_2 emissions in 2019, 8.2 Gt are attributable to the transport sector [3]. The significant share and the fact that the emissions of the transport sector have been steadily increasing in previous years leads to the conclusion that GHG emission analyses of transport are essential to developing measures to counteract these developments.

The countries that ratified the United Nations Framework Convention on Climate Change (UNFCCC) have committed to reporting their national GHG emissions. They do so in accordance with the Guidelines for National Greenhouse Gas Inventories published by the IPCC in 2006 and supplemented and refined in 2013 and 2019 [4–6]. The submission takes place in the course of the National Inventory Report (NIR). The allocation of emissions is carried out according to the so-called 'source principle' which means that emissions are accounted for where they physically occur [7]. This contrasts with the 'cause principle', which allocates emissions to the place where the ultimate benefit (e.g. mobility services) is generated. On the one hand, the strict application of the source principle makes it difficult to identify possible measures to reduce GHG emissions in the application sectors. On the other hand, the mere perspective of the cause principle neglects the possibility to address emission savings in the provision of e.g. materials and energy carriers. Studies in the field of energy system modelling apply the source principle [8–14]. In contrast, the Life Cycle Assessment (LCA) method proceeds strictly according to the cause principle, but mostly evaluates products and services and rarely transport or energy systems. A combination of the tools of energy system analysis and the method of LCA may thus lead to a comprehensive understanding of the interrelationships of the transport sector and the associated GHG emissions. This dissertation shows how the LCA can be integrated into energy system modelling and focuses on the differences between the methods arising from the extension. This is exemplarily applied to the German transport system within the European energy system. In order to embed this in the current state of research, the following chapter looks at existing models that are used for transport emissions accounting.

1.2 Current State of Research

Multiple approaches exist to model transport emissions. Saharidis and Konstantzos [15] give a general overview of possible model concepts. In general, top-down analyses of energy use provide reasonable estimates for CO_2 emissions, while bottom-up transport models are needed for non-CO_2 gases, to allocate emissions to vehicle types and to integrate and evaluate possible emission reduction measures [4]. Bottom-up approaches derive estimates of fuel consumption for different vehicle types based on activity data. These estimates are then coupled with emission factors to derive direct or indirect emissions. Some models also consider vehicle production emissions or include future scenarios. The underlying methodology varies with the scope and goal of each individual model. This chapter contains a description of relevant bottom-up transport emission models to provide the context for the modelling approach in this dissertation.

Two categories of models are distinguished here: national emission models, used for official reporting as explained in Chapter 1.1, and independent models, primarily developed for scientific research. The methodology of official emission models thereby follows the IPCC Guidelines for National Greenhouse Gas Inventories [4]. Their emission factors for energy carriers are country-specific and their energy demand reflects vehicle age, mileage, application, and ambient temperature. The model results include emissions of GHG (CO_2, N_2O, CH_4), air pollutants [CO, NO_x, volatile organic compounds (VOC), particulate matter (PM), NH_3, SO_2], and other toxins such as heavy metals. While independent models are not subject to these formal constraints, they often adhere to the guidelines of the IPCC or draw on similar data sources.

In the following, each model is described in terms of the authors and affiliated institutions involved in its development, its goal and scope, its modelling approach, and its key features. First, four official transport models are presented: three European models (COP-

ERT, TREMOD, and HBEFA Expert) and one from the United States of America (US) (MOVES). Subsequently, four independent models are discussed (GREET, ASTRA, VEU, and THELMA).

COPERT The Computer Program to Calculate Emissions from Road Transport (COPERT) was originally developed in 1989 as a standardised framework for national transport emission inventories in the European Union (EU) [16]. Currently, 21 countries in the EU-27 rely on COPERT and related models for their national emissions reporting [17]. Since the model is freely available, countries outside the EU (e.g. Australia), local authorities, and independent research groups also use COPERT [16]. The Applied Thermodynamics Laboratory of the Aristotle University of Thessaloniki and its spin-off company EMISIA are commissioned by the European Environment Agency (EEA) to develop and maintain the model. COPERT calculates direct emissions for road vehicles with an annual resolution [17]. The current version (5.5) does not consider indirect emissions or emissions from vehicle manufacturing. The methodology follows an average speed approach, i.e., COPERT uses average rural, urban, and highway speeds as inputs to calculate emission factors. The relationships between emissions and speeds are thereby derived from the Handbook of Road Transport Emission Factors (HBEFA) [18], which provides measured emission factors in accordance with the 2006 IPCC Guidelines. In total, COPERT models over 260 vehicle types of passenger and freight transport, defined by vehicle category and subcategory, powertrain, size class, and emission standard. The vehicle types are matched with nine fuel types: petrol, diesel, Liquified Petroleum Gas (LPG), compressed natural gas (CNG), Liquified Natural Gas (LNG), E85, E10, electricity, and hydrogen. Activity data can be provided by the user or purchased from COPERT, which offers datasets for the EU-27 and 10 other countries [19]. The optional SIBYL extension provides historical activity data back to 1970 and baseline projections to 2050. With COPERT street level, EMISIA has further adapted COPERT to study local pollution levels, e.g., to identify or monitor urban hotspots [20].

TREMOD The Transport Emission Model (TREMOD) was developed by the Institute for Energy and Environmental Research (IFEU) on behalf of the German Environmental Agency (UBA) [21] for emissions reporting in Germany. The model is not available for public research, and access to it is restricted to the consortium commissioned with its development. TREMOD calculates both direct and indirect emissions for different modes of transport with annual resolution. In the current version (6.0), emissions during vehicle production are not considered. Its methodology follows the traffic-situational approach of the HBEFA whereby emission factors are calculated as weighted averages based on German traffic data. The model scope includes road, rail, air, and inland waterway transport [21]. The level of detail in road transport corresponds to that of COPERT [16]. Rail transport is differentiated into passenger, freight, and shunting trains with electric or diesel drivetrains. In air transport, a distinction is made between passenger and cargo aircraft on domestic or international routes.

The modelling of inland waterway transport is limited to freight vessels with diesel engines. The supplementary Mobile Machinery model (TREMOD-MM) provides an option to add non-road vehicles (e.g., for construction or agricultural uses). The activity data is sourced from federal statistics [Federal Motor Transport Authority (KBA), DESTATIS], the Deutsche Bahn, and the Öko-Institut [22]. The results provide estimates for emissions between 1950 and 2050. TREMOD thereby allows researchers to benchmark future mitigation scenarios against a baseline scenario. Data from TREMOD feeds into official statistics, life cycle assessment databases (e.g. ecoinvent), and tools for comparing the emissions of transport modes (e.g. EcoPassenger).

HBEFA Expert Model The Handbook of Road Transport Emission Factors was first developed in 1995 on behalf of the Federal Environmental Offices of Austria, Germany, and Switzerland [23]. The Swiss research institute INFRAS is responsible for its development and maintenance. Today, the HBEFA contains country-specific emission factors for Germany, Austria, Switzerland, Sweden, Norway, and France [18]. Since 2014, a separate version has been developed for China [24]. Two versions of the HBEFA database exist, namely a public version that is available for a fee and an expert version that is reserved for companies and individuals involved in the development of HBEFA. Only the expert version contains a supplementary fleet model that allows researchers to perform inventory-based emission calculations. The expert version is currently used to prepare national inventories in Switzerland, Sweden, Liechtenstein, and Monaco [16]. It has also been used in assessing policy measures [25] and for environmental impact assessments of the Swiss passenger transport sector [26]. The model calculates direct emissions of road vehicles in annual resolution between 1990 and 2050. The current version (4.2) does not include upstream emission factors for fuels or vehicles. Vehicle and fuel types in the model correspond to the classification of road vehicles in TREMOD. The methodology follows a traffic-situational approach by calculating emission factors as weighted averages based on country-specific traffic data. The underlying activity data is defined as a mix of 276 predefined traffic situations, e.g., urban stop and go on a main road [16]. Each situation translates to a distinctive driving pattern based on real driving behaviour. The results go beyond the scope required by the IPCC guidelines, e.g., by including emissions at the regional and local levels.

MOVES The Motor Vehicle Emission Simulator (MOVES) is used by the United States Environmental Protection Agency (EPA) to create transport emission inventories and was originally released in 2010 [27]. The geographic scope covers the US, including Puerto Rico and the Virgin Islands. Besides emissions reporting, the model is also used to evaluate mitigation policies [28] and future scenarios [29]. MOVES is freely available, but since it is country-specific, it is of limited use for analyses outside the US. It calculates the direct tailpipe emissions of road and non-road vehicles with an hourly resolution and air, rail, and commercial maritime transport are not considered [27]. The methodology follows a multi-scale approach which means it calculates emissions as a function of engine power demand, based on multiple measurements, e.g., onboard and stationary [15]. Road vehicles include 13 categories of cars, motorbikes, motor homes, buses, and trucks. Off-road vehicles are modelled along 12 economic sectors, e.g., bulldozers in construction or harvesters in agriculture. MOVES does not distinguish between different hybrid drivetrains and approximates energy consumption rates for electric vehicles from petrol and diesel vehicles. The modelled fuel types are petrol, diesel, CNG, electricity, and E85 [27]. The hourly results are differentiated by weekdays and weekends for each month in 1990 and from 1999 to 2060 and can be aggregated to show daily, monthly, or yearly results on either a national, county, or project scale, thereby allowing the model to be used for both macroscopic and microscopic analyses [30].

GREET The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is a life-cycle analysis tool to study the emissions and energy use of transportation in the US [31]. The Argonne National Laboratory, funded by the Department of Energy, has been developing the model since 1995 [32]. The model is freely available as both a program with a graphical user interface and in the form of Microsoft Excel spreadsheets [33]. Both public and private institutions use GREET, e.g., to evaluate the sustainability of current and future vehicle-fuel pathways [34]. The model consists of two modules: GREET 1 for fuel cycles and GREET 2 for vehicle cycles [31]. Together, they evaluate the total impact of transportation, i.e., direct (tank-to-wheel) and indirect (well-to-tank) emissions in the use phase of vehicles and the emissions from vehicle production, maintenance, and end-of-life processes. The modelled emission types include GHGs, air pollutants, and particulate matter. In addition, GREET also tracks impacts on energy and water use. The methodology in GREET follows the ISO guidelines for attributional life cycle assessments defined in ISO 14040 and 14044. Therefore, life cycle inventories are compiled for each vehicle type under US conditions. Its system boundaries include all operational activities while excluding infrastructure-related activities [32]. The model covers all major transportation sectors (road, rail, air, and water), while offering a wide range of vehicle and fuel types [31]: various types of light, medium, and heavy duty road vehicles, passenger and freight trains and aircraft, and ocean and inland vessels are modelled. Over 80 combinations of road vehicles and fuel systems are available in GREET. In addition to the powertrain options that are also featured in COPERT, GREET further considers methanol fuel cells and fuel cell systems with onboard hydrocarbon-to-hydrogen reforming. The available fuel types range from petrol, diesel, LPG, and LNG to methanol, ethanol, dimethyl ether (DME), and hydrogen. GREET thereby models over 100 fuel-production pathways from both conventional and renewable feedstock sources. The necessary activity data and vehicle characteristics are drawn from Autonomie, Argonne National Laboratory's vehicle system simulation tool [35] while the emission factors for petrol and diesel vehicles are derived from the national emissions model MOVES [36]. The resulting life cycle impacts can subsequently be calculated for each vehicle type and year, either per service unit (e.g., passenger-kilometre), energy output (e.g., MJ), or resource input (e.g., kg natural gas).

ASTRA The Assessment of Transport Strategies (ASTRA) model is a system dynamics model of transport and energy policy scenarios in Europe [37]. Originally created in 1997, the latest version, ASTRA 2.0, is developed and maintained by the Fraunhofer-ISI Institute Systems and Innovation Research in collaboration with the consultancies Trasporti e Territorio and M-Five. The geographical scope covers the EU-27 and the United Kingdom (UK), Norway, and Switzerland. Dedicated national versions of the model exist for Germany (ASTRA-DE) and Italy (ASTRA-IT) with a spatial resolution on the NUTS-II level. It was recently used to develop the so-called *Langfristszenarien* (long-term scenarios) of the German transport sector on behalf of the German Federal Ministry for Economic Affairs and Climate Action [38] for which the modelled timeframe ranges from 1990 to 2050. ASTRA provides a wide range of transport, economic, social, and environmental indicators. These include indirect and vehicle production emissions of GHGs and air pollutants. Following a system dynamics approach, ASTRA combines nine modules to reflect interdependencies between population, economy, trade, transport demand, vehicle fleets, and the environment [39]. In essence, the economy, trade, and population modules define the total transport demand for each year. This demand is then converted into traffic performance for different modes of transport and finally allocated to vehicle types according to the estimated vehicle fleet composition. The total emissions are calculated using fleet-average traffic-adjusted emission factors while the underlying activity data is derived from traffic surveys, as published by the German Federal Ministry for Digital and Transport [40]. The model covers passenger road transport in addition to freight transport on roads, rail, and inland waterways. Road vehicles are further divided into cars, buses, light duty vehicles (LDVs), mid duty vehicles (MDVs), and heavy duty vehicles (HDVs) with different spatial domains (short- and long-distance), emission standards, and drivetrain technologies. The modelled powertrains include four conventional (petrol, diesel, CNG, LPG) and three electrified options [battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), fuel cell electric vehicle (FCEV)]. Due to the system dynamic approach, policy measures and effects beyond the transport sector can be assessed. The modular design further allows for the coupling of ASTRA with other models to create more complex scenarios, e.g., with agent-based modelling of vehicle purchases [38]. At the same time, the approach limits all results to the country level and macroscopic analyses.

VEU In the Traffic Development and Environment (VEU) project, researchers from the German Aerospace Centre (DLR), the Helmholtz Centre Hereon (HZH), and the Karlsruhe Institute of Technology (KIT) created a spatially and temporally refined transport emissions model for Germany [41]. The project was funded by the German Federal Ministry for Economic Affairs and Climate Action to investigate the impacts of transportation on humans and the environment [42]. Besides evaluating current emissions, the consortium presents three scenarios for 2040: Reference, Free Play, and Regulated Shift. VEU calculates direct emissions of road, rail, air, and inland water transport and indirect emissions of electricity in hourly resolution. The emission types that are considered include GHGs as well as air pollutants, particulate matter, and noise emissions. [43] The methodology for calculating direct emissions in road transport resembles the average speed approach in COPERT: VEU couples transport demand and vehicle technology models to derive emissions by road type (urban, rural, and highway) for a representative meteorological year. Using the SMOKE emissions modelling system [44], the emissions are then allocated to a 5 × 5 km grid of Germany's road, rail, and inland waterways network. Modelled passenger road vehicles include small, medium, and large cars and urban buses and coaches. Road freight is modelled for light-, medium-, and heavy-duty vehicles and semi-trailers [41]. It models three conventional (petrol, diesel, CNG) and six electrified powertrain options (diesel-hybrid electric vehicle (HEV), petrol-HEV, diesel-PHEV, petrol-PHEV, BEV, and FCEV). Rail transport is divided into urban, regional, and long-distance passenger and freight trains, with either electric, diesel, or fuel cell powertrains. Water and aviation vehicles are not subdivided further. The emission factors for conventional road vehicles are taken from the HBEFA and GEMIS databases, supplemented by factors for particulate matter and extrapolated further into the future. Additional emission factors were determined for HEVs, PHEVs, and BEVs [45]. Rail and inland water transport are evaluated based on the TREMOD results [22]. The results can be aggregated to the desired spatial and temporal resolution. This facilitates the mapping of pollution hotspots and the estimation of the health risks and environmental damage caused by current and future transport in Germany. GHG emissions are thereby typically reported at the country level, as their impact is independent of the spatial distribution [41].

THELMA In the Technology-centred Electric Mobility Assessment (THELMA) project, a joint research group from the Paul Scherrer Institue (PSI), the Eidgenössische Technische Hochschule Zürich (ETHZ), and the Swiss Federal Laboratories for Material Science and Technologies (EMPA) received funding from the Swiss Competence Centre for Energy Research (SCCER) to conduct an integrated assessment of passenger vehicle electrification in Switzerland [46]. Consequently, the study reflects Swiss conditions and projected developments until 2030. The goal was to provide comprehensive, cradle-to-grave cost-benefit analyses of future vehicle technologies in Switzerland. Therefore, THELMA evaluates impacts on the environment, economy, society, security of energy supply, and driver utility using a multi-criteria decision analysis and a total cost analysis [46]. The main indicator for environmental impacts is total vehicle emissions, derived from LCA. The reported emissions include GHGs, air pollutants and particulate matter. Direct use-phase emissions are derived from the energy demand in simulated drive cycles based on the activity data from the Swiss Federal Statistics office while indirect emissions of electricity are defined as a function of the power plant mix. This use-phase data is then integrated into the life cycle inventories of vehicles to calculate the up- and downstream emissions of vehicles and fuels. In line with ISO 14040 and 14044, all vehicles are modelled as combinations of standardised life cycle inventories from the life cycle database ecoinvent [47]. Within a given vehicle type, all non-drivetrain-specific components remain identical to create a common basis for technology comparisons. Initially, THELMA focused on seven passenger vehicle types, however, the methodology has since been applied to a wide range of road vehicles, e.g., in a consecutive study on urban transport that was conducted on behalf of the city of Zurich [48]. As a result, comparable life cycle inventories now exist for bicycles, scooters, small, medium, and large cars, vans, urban, regional, and long-distance buses, light-, medium- and heavy-duty trucks and semi-trailers. The considered powertrains include conventional combustion engines (petrol, diesel, and CNG) and electrified systems (HEV, PHEV, BEV, FCEV). Fuels from fossil (oil, natural gas) and renewable sources (biogas, biodiesel), different electricity mixes, and four hydrogen generation pathways are modelled [46]. The results of THELMA and related projects have been merged into the open-source life cycle assessment tool premise, which provides a web application and a Python package to compare current and future road vehicles [49]. Thereby, the timeframe extends to 2050 and the methodology includes modifications of the background database according to future energy policy scenarios [50].

1.3 Objective and Research Questions

As shown throughout this chapter, official emission models have been refined to reflect direct emissions and rebound effects in the respective countries, while independent models often dive deeper into the upstream emissions of individual vehicle types. Especially for GHG emissions, the territory principle behind national emissions models restricts their explanatory power regarding the real environmental impacts of transportation. At the same time, independent models that include a life cycle perspective are often performed on an individual vehicle level, thereby disregarding the systemic effects of fleet-based scenarios or limiting the analysis to certain modes or areas of transportation.

Between the systemic approach of national reporting models and individual technology assessments exists a methodological gap that combines both layers of complexity. In part, although this gap has been addressed for Switzerland in THELMA and subsequent studies, their results cannot be directly transferred to Germany and also lack an analysis of the relationship between the behavioural and technological developments in future transportation.

In order to fill this gap and to compare the evaluation that this entails, the objective of this dissertation is to develop a model of the transport sector that is capable of assessing transport emissions by means of two different methods. On the one hand, the tools of energy system analysis will be used, which, similar to the guidelines of the IPCC, focus on energy-related emissions. On the other hand, the assessment is to be extended to include a life cycle perspective and thus integrate non-operational emissions such as e.g. the production of vehicles or energy conversion plants. Thereby, the transport sector is embedded in an energy system that aims to reach certain GHG emission reduction goals. Besides the modelling aspects and the results for the transport and energy sector, the focus will be on the differences between the two emission accounting methods.

In concrete terms, this results in the following research questions:

- How can the transport sector be modelled in the context of a dynamic energy system?
- What challenges arise with the integration of life cycle assessment in transport sector modelling and how they can be addressed?
- How does the development of the transport sector affect the goal of a drastic reduction of GHG emissions in the whole energy system?
- What additional emissions arise in the assessment through the integration of a life cycle perspective and how might this develop in the future?
- How do the two methods used for emissions accounting differ and for what purpose can they be considered?

2 Methodologies for Evaluating the Ecological Impact of the Transport Sector

To answer the research questions formulated in Chapter 1.3, the methodology in Figure 2.1 was developed. It shows the general elements of the methodology and its components as well as the structure of the dissertation.

Discussion of the Transport Sector and Development of Transport Scenarios The fundamentals of the transport sector and the input for the further modelling approaches are described in Chapter 3. First, a general overview of the structure and historical development of the sector is given. A meta-analysis of existing system studies is used to examine which developments in the transport sector are considered relevant. This forms the basis for the development of transport scenarios, which are separated into mobility and technology scenarios and are parameterized and prepared for input into the model. Thereby, two mobility scenarios and two technology scenarios are examined. In the mobility scenarios, a distinction is made between a conventional scenario and a scenario that follows a strongly multimodal approach with a significant increase in the use of car sharing. The technology scenarios are differentiated between a scenario that continues to predominantly rely on vehicles with combustion engines and a scenario that assumes drastic electrification in all transport areas.

Dynamic Transport Sector Modelling The core of the modelling part is the Transport Model (TraM). With the help of mobility demand and technology shares, the required fleet for the respective scenarios is calculated. The result of the energy consumption is passed on to the linear energy system optimization model Integrated Simulation Model for Planning the Operation and Expansion of Power Plants with Regionalisation (ISAaR), which subsequently calculates the coverage of the energy demand in a cost-optimal way. In this way, possible repercussions for the energy system and the increased necessary expansion of renewable energies are taken into account. Based on this, the GHG emissions can be derived according to the System-Dynamic Assessment (SDA) method and the costs of the transport sector.

Life Cycle Data Expansion and Inventory The tools of energy system modelling are complemented by a life cycle perspective. In accordance with the LCA method, the goal and scope of the study are first defined and the Life Cycle Inventory (LCI) is integrated as the data

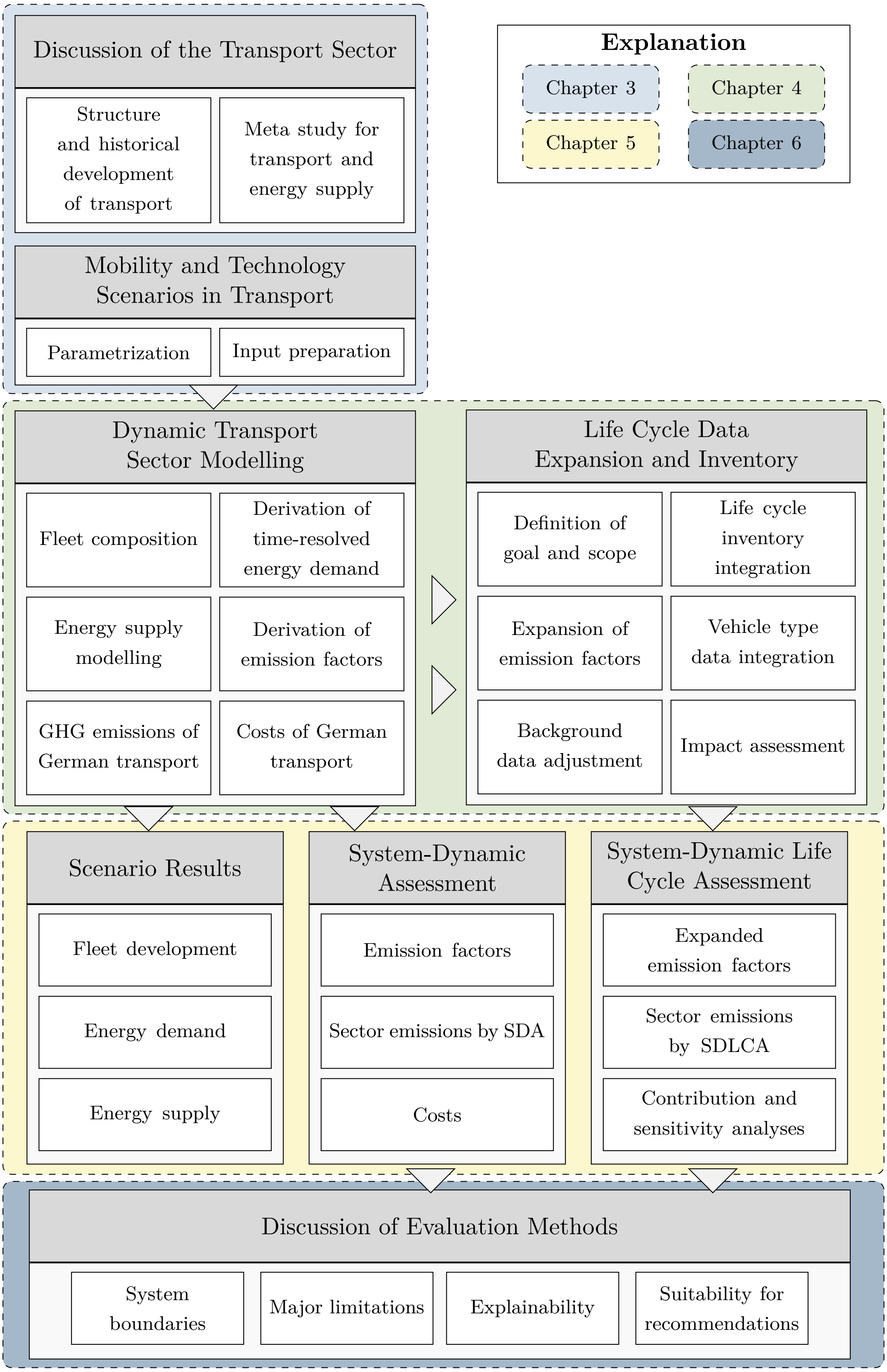


Figure 2.1: Structure of this dissertation and its underlying methodology

basis for further processing. The LCI represents the essential data basis for the calculation of the LCA and in the present case contains information on the production and end-of-life of vehicles. In the process, it is adapted to the German transport sector. The emission factors, which were initially developed in the course of the transport sector modelling, are expanded in this course to include their upstream chain. This includes the acquisition, extraction, and transport of energy carriers and the construction of energy conversion plants such as e.g. photovoltaic plants. Before the impact assessment takes place, the data basis for the scenario years is adjusted in the course of the prospective LCA with the help of background scenarios. In combination with the dynamic modelling of the transport sector, the method is referred to as the System-Dynamic Life Cycle Assessment (SDLCA).

Scenario Results The general transport results, which are equal for both of the following evaluation methods, are provided in Chapter 5.1. They describe the development of fleet stocks and the related energy demand. The contributions of the individual transport and energy carriers to the total energy demand and its temporal resolution are discussed in detail. The chapter also describes how the energy supply must subsequently adapt to the development of the transport sector while complying with an emission cap.

System-Dynamic Assessment Chapter 5.2 presents the results of the SDA. First, the emission factors of the energy carriers used in the transport sector for the four scenarios are outlined and discussed. The total sector emissions are explained in detail and specific emissions and contributions to the total emissions of the vehicle types are presented. An investigation of the total costs and the influence of different mobility approaches or technology developments completes the chapter. Specific values for the vehicle types are also provided in the section on costs.

System-Dynamic Life Cycle Assessment The results of the SDLCA are displayed and discussed in Chapter 5.3. The expanded emission factors and their differences compared to the SDA are explained first. Furthermore, the differences in the total operational emissions of the transport sector based on the change of emission factors are described. Moreover, the total emissions of transport, including the non-operational emissions, provide information on the relevance of the integration of the life cycle perspective in the ecological assessment. Contribution analyses of the non-operational emissions are provided to ensure a better understanding of the results of the SDLCA. A sensitivity analysis at the end of the chapter examines the relevance of the location of battery production for the total emissions.

Discussion of Evaluation Methods In Chapter 6, the methods of SDA and SDLCA are compared and discussed on a general level. First, the system boundaries and the extent to which they are comparable with established emission reporting methods are discussed, after which the major limitations are presented. These include the general limitations of the underlying model as well as limitations specific to the two emission evaluation methods. The evaluation of the explainability of the methods serves as the final basis for the discussion of the suitability of the recommendations for action. This addresses the question of which method is suitable for recommending actions for specific stakeholders.

Finally, based on the results, answers to the underlying research questions are provided in Chapter 7 and areas of further research in the context of comprehensive transport emission assessment are provided.

3 Developments in Transport

The aim of the chapter is to provide a general overview of the transport sector and to highlight possible trends and developments for the future. For this reason, it first gives a basic description of the transport sector and its components (Chapter 3.1). The structure of the sector and the related terms and definitions are further explained. The historical development of the sector is described before shifting the focus to the future and analysing scenarios from the literature in Chapter 3.2. Finally, in Chapter 3.3 the scenarios to be evaluated are described and their basic framework assumptions and data are presented. Chapter 3.4 gives a general conclusion to classify further steps in scenario modelling and evaluation.

3.1 The Transport Sector

Transport is the change of the location of objects such as persons, goods, and information in a defined system [51]. Starting with this definition, in the following, the terms of the sector are explained and defined for further use. Possible forms of transport will be discussed and new forms of transport that may emerge in the future will be described. Afterwards, the historical development and the associated transport performances are discussed. The development of energy consumption and the associated emissions of the transport sector are also described in the context of the total emissions in Germany.

3.1.1 Definitions and Structure of the Sector

The transport sector is divided into the transport areas of passenger transport and freight transport. By definition in this dissertation, the transport areas are further subdivided into respective transport modes. These transport modes include road transport, rail transport, air transport, shipping, and pipeline transport. The transport modes can, in turn, be served by different transport types with different drivetrains. These transport types can also be subject to different usage modes as there are transport types that are used privately and ones that are shared. The combination of one transport type with a certain propulsion system is further called a vehicle type.

This dissertation focuses on domestic traffic in Germany and thus excludes international shipping. In addition, pipeline transport is assigned to the energy infrastructure and is thus not included in the transport sector. In the case of international air traffic, all flights departing from Germany are included due to their energy consumption in Germany. Figure 3.1 lists the transport areas, transport modes, and vehicles considered in this work. There are several drive options for each technology, which can differ in terms of the energy carrier required, specific energy consumption, and other parameters such as service life or annual mileage.

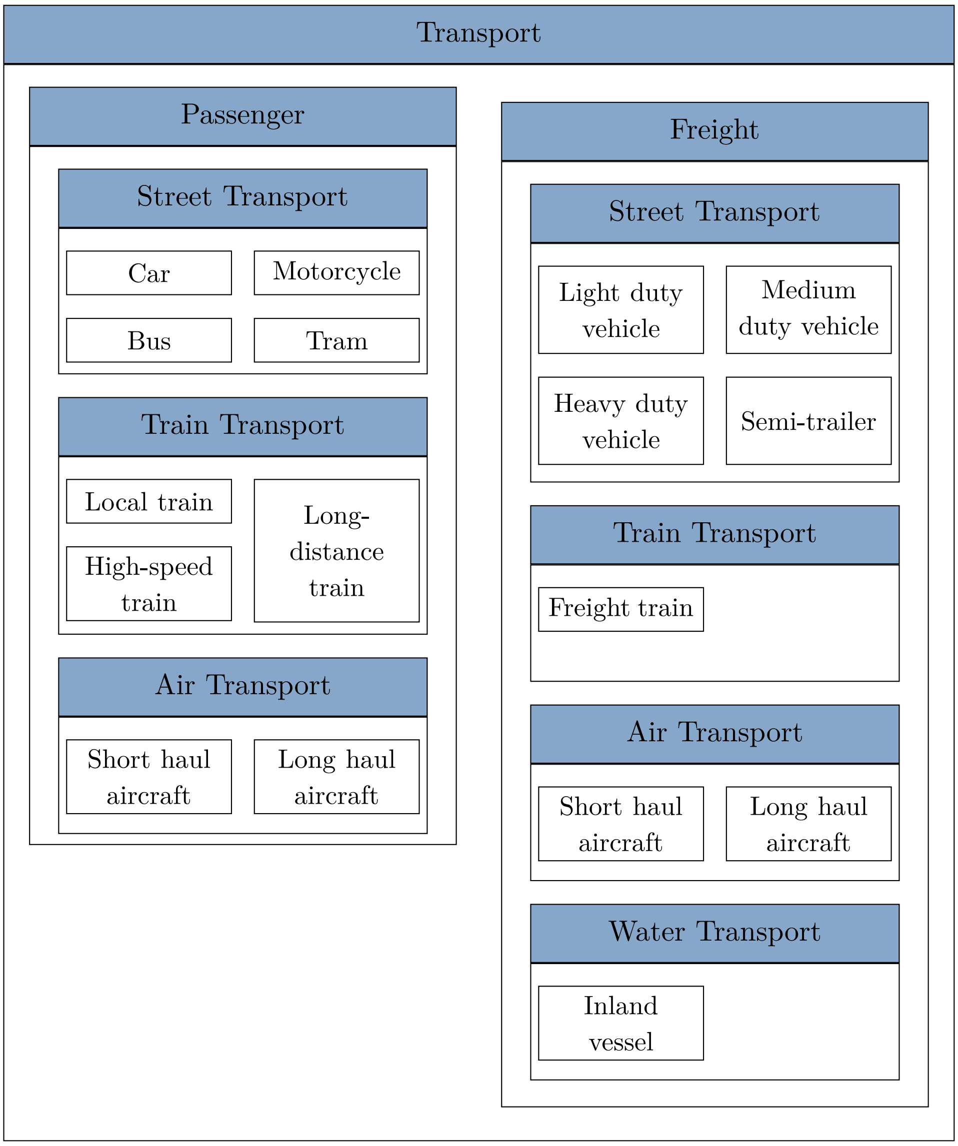


Figure 3.1: Division of the transport sector into areas of transport (e.g. passenger transport), modes of transport (e.g. street transport) and transport types (e.g. cars)

In order to get a sense of the important parameters and trends in the sector, some points that are relevant for further understanding are discussed below.

Powertrain Systems The conventionally used powertrains in road transport are diesel and petrol engines, while both diesel and electric motors are used in train transportation. In inland navigation, ship engines are powered by diesel and aircraft traditionally use jet fuel in turbines. There are many alternatives for the propulsion of road transport vehicles. For example, natural gas can be used in gas engines and it can both be used as CNG and LNG. Electric propulsion systems are also used in the car segment. This can be done by using BEV, which are purely powered by electricity, as well as hybrid variants. The hybrids have both an electric motor and an internal combustion engine installed whereby a distinction is made between those that can be charged with an external source (PHEV) and those that cannot (HEV). The final alternative is the FCEV which is powered by hydrogen. In addition to the conventional drives for trains mentioned above, the fuel cell is also used as a possible alternative in individual projects [52]. The use of hydrogen in aviation is also being discussed [53]. For inland and coastal navigation, although different approaches are being pursued with hydrogen and batteries, the use of diesel is still predominant in the medium term [54].

Conventional and Alternative Fuels The energy supply of the transport sector is currently based, to a large extent, on the combustion of fossil hydrocarbons. The main energy sources that are used are diesel, petrol, and jet fuel. These energy sources can also be obtained from renewable energies. For example, diesel and ethanol from biogenic sources are already being used in conventional engines today [55]. Additionally, the use of renewable electricity for fuel production is also seen as a way of defossilising transport. Electricity can be used to produce various fuels, which can either be used as drop-in fuels or blends. These include Fischer-Tropsch fuels (FT fuels), polyoxymethylene dimethyl ether (OME), DME, or methanol [56].

Usage A further classification of the technologies can be made according to individual and public transport. In passenger transport, only the use of cars and motorcycles would be considered individual transport and this is known as motorised individual transport (MIT). All other means of passenger transport are assigned to public transport. The transport of goods on the road by truck can also be called MIT. In addition to the known types of use, car sharing represents a type of transport that includes both individual and public transport aspects. Here, motorised individual transport is carried out, but with the help of vehicles that are available to everyone. In this context, a distinction is made between station-based (SB) car sharing and FreeFloating (FF) offers. SB car sharing is based on the principle that a rented vehicle is returned to specific locations after it has been rented. On the other hand, with FF car sharing, vehicles can be parked at any public parking lot within the operator's business area. Currently, however, only a very small portion of the traffic volume is allocated through car sharing [57].

Autonomous Driving In addition, a further development is emerging in road traffic, the effects of which can be disruptive in terms of how mobility is viewed. Autonomous driving describes the ability of a vehicle to take over the activities of the driver. Based on the level of autonomous driving, it can either be seen as support or full automation. Depending on the degree of automation, new parameters can arise in terms of mobility behaviour and energy consumption. For example, autonomous driving can be used to enable trucks to drive very close behind each other on highways. This so-called pooling leads to lower energy consumption due to lower aerodynamic drag. On the other hand, a very high degree of automation can also result in trips being made that would not have been made otherwise and thus a higher mobility requirement would therefore also be accompanied by a higher energy requirement. Gyetko et al. [58] give an in-depth discussion related to the potential effects of autonomous driving technologies on road transportation. Due to the large uncertainties regarding the development and its associated effects, a more detailed consideration of autonomous driving is not included in the scenarios in this thesis. However, it should be mentioned that this technology, in combination with car sharing, has the potential to drastically reduce the vehicle stock [58].

3.1.2 Historical Development of the Sector

For the analysis of the development of the transport sector in terms of energy consumption and GHG emissions, the indicators of transport performance and specific energy consumption are of particular significance. Their history will now be examined in more detail.

Transport Performance Transport performance describes the change in location of a person or freight by a certain distance. Depending on whether it is passenger or freight transport, the transport performance has the unit passenger-kilometre (pkm) or tonne-kilometres (tkm) [51]. The statistics for German transport performance according to the territorial principle go back to 2002. Since then, passenger transport performance in Germany has remained approximately constant. In 2019, the transport performance was 1,169 bn pkm. Of this, 78.5 % was derived from private motorised transport, and the other modes of transport such as rail (100 bn pkm), public road transport (79 bn pkm), and air transport (72 bn pkm) each have smaller shares. The structural distribution also remained roughly the same over the period from 2002 to 2019. The situation is different for freight transport. In the years between 2002 and 2019, freight transport increased by 36 % from 516 bn tkm to 702 bn tkm. In particular, transport by rail and road has increased. However, road transport also plays the most important role in freight transport with 499 bn tkm. The other modes of transport besides rail (133 bn tkm) are inland navigation (51 bn tkm), air freight (2 bn tkm), and transport via pipelines (18 bn tkm). [59]

Specific Energy Consumption The specific energy consumption in transport is usually expressed in terms of energy per kilometre travelled. For passenger cars, this is also given in volume per 100 km and is therefore expressed with the unit $\frac{l}{100km}$. However, in order to compare different means of transport with regard to their efficiency, the relation of energy to transport performance is decisive. Thus, either the unit $\frac{J}{pkm}$ respectively $\frac{J}{tkm}$ or $\frac{Wh}{pkm}$ respectively $\frac{Wh}{tkm}$ is used.

The data underlying Figure 3.2 are published by the UBA and are based on the TREMOD data and calculation model [22, 60]. Depending on the transport type, different trends are emerging in passenger transport. Since 1995, there has been a decline in the use of planes, trams, and subways as well as trains. From 2012 onwards, coaches have been added to the evaluation and represent the most efficient mode of travel in 2019. In this context, coaches are the buses that cover long-distance scheduled routes and which have to be distinguished from travel buses that are booked for special trips. The specific emissions of these and public buses increased in the period under consideration. Although the publication does not give any indication of the background, it can be assumed that this is due to the decreasing capacity utilisation. In the case of cars, the specific energy consumption has remained approximately the same. The increase in efficiency over this period was outweighed by the increase in engine power [59] although this is not the case for the whole EU. While vehicle masses in the EU have increased, both the average engine displacement of vehicles and their consumption have decreased over the entire period. In the years since 2016, however, consumption has again risen slightly [61]. With the exception of air travel, all means of public transport can be classified as being more efficient than the car which, in part, is due to the higher occupancy rates. Especially in long-distance transport, the occupancy rates are always higher than 50 % [62]. In the passenger car, on the other hand, the average occupancy rate lies at 1.4 persons [59].

In freight transport, the specific consumption of road transport is also significantly higher than that of the alternatives. However, the greatest efficiency gains in road transport, namely at 26 %, were also recorded over the period from 1995 to 2019. These modes of transport bear the cost of the lower specific energy consumption of rail and water transport with less flexibility, as they are tied to railways and waterways respectively.

Total Energy Consumption The combination of the transport performance and the specific energy consumption thus leads to the total energy consumption. The historical development of the energy consumption of the transport sector is presented in Figure 3.3. The comparatively high specific consumption and high transport performance result in the largest share of energy consumption being attributable to road transport. In 2019, 57 % of energy consumption was attributed to road passenger transport (of which 2 % is derived from public transport) and 25 % to road freight transport. A further 16 % is attributable to air transport and 2 % to rail transport. Inland navigation is responsible for less than 1 %.

While private road passenger transport has remained the same in the period under consideration, the situation is different for road freight transport as its energy consumption declined until 2009 and has risen steadily since then. However, the total energy consumption of 192 TWh is still 14 % below the value from the year 2000. In contrast, the energy consumption of rail

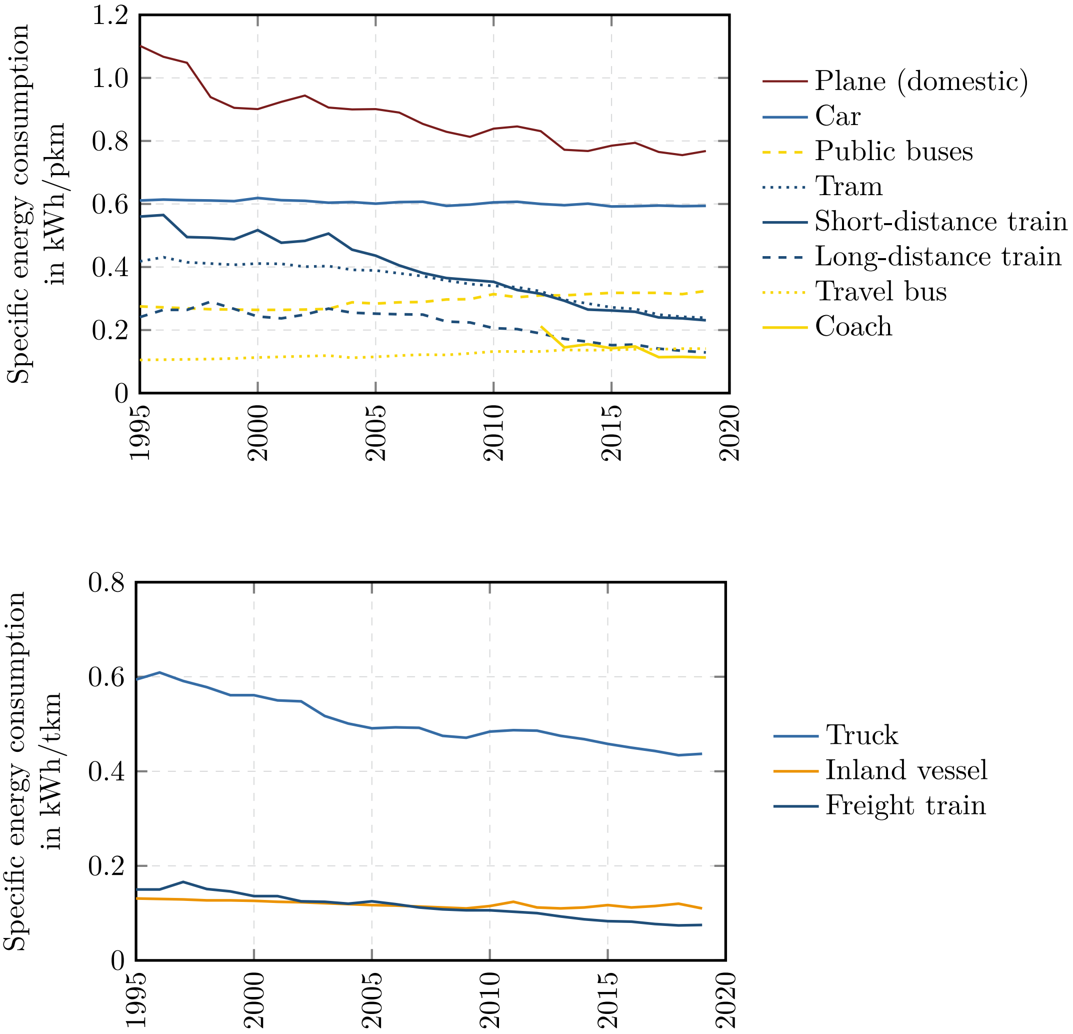


Figure 3.2: Specific energy consumption of different modes in passenger (top) and freight (bottom) transport [22, 63]

transport is strongly declining, although the transport performance in passenger and in freight transport has increased. This is due to progressive efficiency gains (Figure 3.2).

Of the energy consumption in 2019, 94 % is due to the burning of oil-based fuels such as petrol, diesel, and jet fuel. Another 4 % are bio-based fuels and 2 % electricity, which is almost entirely due to rail traffic. [59]

Propulsion Systems in Cars From 1960 to 2021, the number of registered cars in Germany has increased from 4.5 million to 48.2 million vehicles. Both in 1960 and now, the majority of vehicles are powered by combustion engines. As of 1 January 2021, 31.4 million vehicles were registered with petrol engines and 15.1 million with diesel engines. The sum of both drives corresponds to a share of 96.5 % of cars in Germany [64]. Furthermore, in 2021 there are also vehicles in the transport system that are powered by LPG and CNG, although these represent

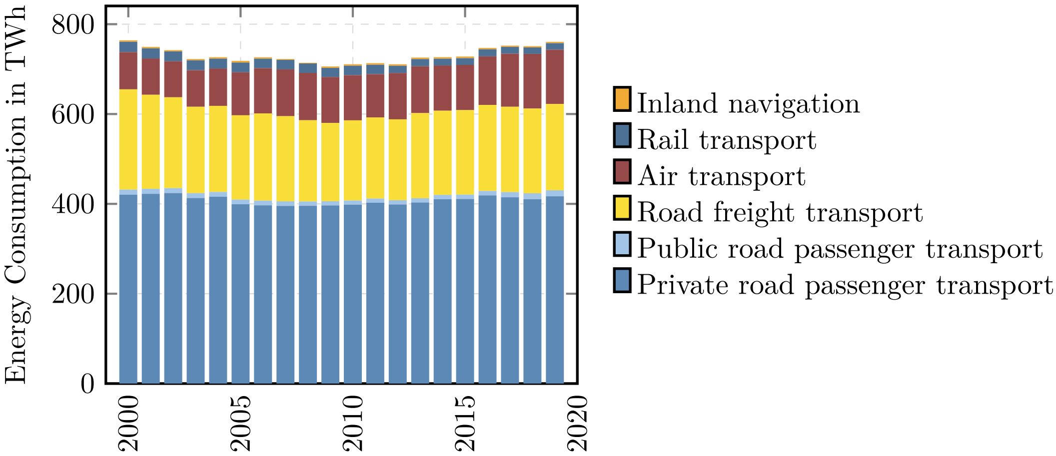


Figure 3.3: Overview of the historical energy consumption by mode of transport [59]

a very small part of the total with 0.3 million and 0.1 million vehicles respectively. Moreover, the number of vehicles with such drives is stagnating. Electric vehicles also represent only a small part of the car fleet at the beginning of 2021. Thus, 1.0 million HEVs, which include 0.3 million PHEVs and 0.3 BEVs are driving on Germany's roads as of the reporting date [64]. Although the inventory figures do not suggest a change in the system, looking at the developments in new registrations in recent months and years, one can assume that a shift towards more vehicles with electric drives will take place. As can be seen in Table 3.1, the shares of BEVs and PHEVs have recently risen sharply [65]. In particular, the number of new registrations significantly increased from 2020 onwards whereby the reason for this can potentially be attributed to the increasing number of electric vehicle models available from car manufacturers and the increased purchase subsidy. The incentive for BEVs was increased from 4,000 € to up to 9,000 € and for PHEVs from 3,000 € to up to 6,750 € [66].

Table 3.1: New car registrations in Germany in the last 6 years [65]

		Total		Share	
	Total registrations	BEV	PHEV	BEV	PHEV
2016	3,351,607	11,410	13,744	0.3 %	0.4 %
2017	3,441,262	25,056	29,436	0.7 %	0.9 %
2018	3,435,778	36,062	31,442	1.0 %	0.9 %
2019	3,607,258	63,281	45,348	1.8 %	1.3 %
2020	2,917,678	194,163	200,469	6.7 %	6.9 %
2021	2,622,132	355,961	325,449	13.6 %	12.4 %

The number of total new registrations has fallen sharply in the last 2 years and it remains to be seen whether this reflects a trend or whether it remains an exception. Nevertheless, the number of approximately 3 million new registrations per year shown in Table 3.1 is to be considered very high in relation to the absolute number of vehicles in the stock. As a result, within a few decades, the passenger car sector could theoretically be transformed. [9]

3.1.3 Historical Emissions of the Sector

To round off this section, the historical development of GHG emissions will be examined in more detail. In the national trend tables for German atmospheric emissions, the UBA shows GHG emissions in Germany dating back to 1990 [60]. Especially with regard to political goals, 1990 represents an important year. For example, it is used in the Kyoto Protocol as the base year for emission reductions [67] and Germany's emission reduction targets are also based on this year.

In order to be able to classify the relevance of emissions in transport, the total emissions in Germany and their development in recent years are first discussed. As can be seen in Figure 3.4, Germany had a total amount of GHG emissions of 1,249 Mt CO_2e in 1990. Most of this was due to the energy industry which emitted 466 Mt CO_2e. In addition, the areas of industry (284 Mt CO_2e), buildings (210 Mt CO_2e), and transport (164 Mt CO_2e) were responsible for large amounts of GHG emissions. Agriculture and waste contributed smaller amounts of 87 Mt CO_2e and 38 Mt CO_2e respectively. Between 1990 and 2021, total GHG emissions have been reduced by 39.0 % [60]. Thereby, it is above all the energy sector that is undergoing constant change and successively reducing emissions. The steady increase in renewable energies in power generation is largely responsible for this as shown by the fact that emissions in the energy sector fell by 47.0 %. In addition, emissions from industry fell by 36.2 % and from buildings by 45.2 %. The transport sector has only 9.7 % less GHG emissions in 2021 than in 1990.

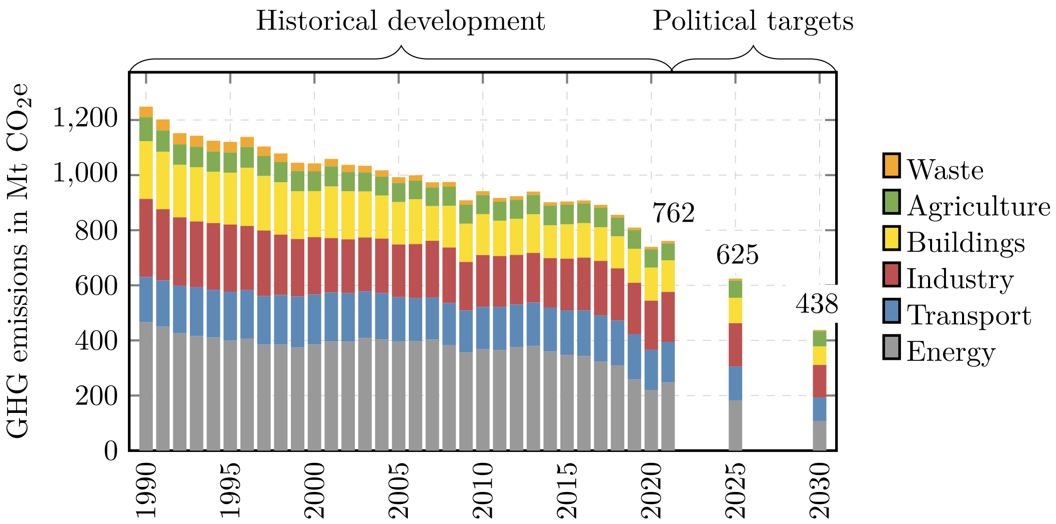


Figure 3.4: Historical development of GHG emissions in Germany [60] and political targets [68]

With the amendment of the Climate Protection Act in May 2021, the German government plans to reduce GHG emissions to a maximum of 35.0 % of 1990 levels by 2030. In addition, net GHG neutrality is to be achieved by 2045. Sector targets have also been set. By 2030, the energy industry must reduce its emissions by 76.8 % compared to 1990, industry by 58.4 %, buildings by 68.1 %, and the transport sector by 48.1 %. Although the necessary emission reduction in the transport sector can be considered as being low, the targets are ambitious in light of the development in the last decades. [68]

Upon a closer examination of the transport sector, it becomes apparent that the largest shares of GHG emissions arise from road transport. Figure 3.5 thereby only shows the GHG emissions that are also relevant to the goals of the German Federal Government and thus international air traffic is not included here. In 2021, 98.0 % of emissions in the transport sector are attributable to road transport. Of these, 31.9 % are attributable to freight transport, 2.1 % to public passenger transport, and 66.0 % to individual motorised transport.

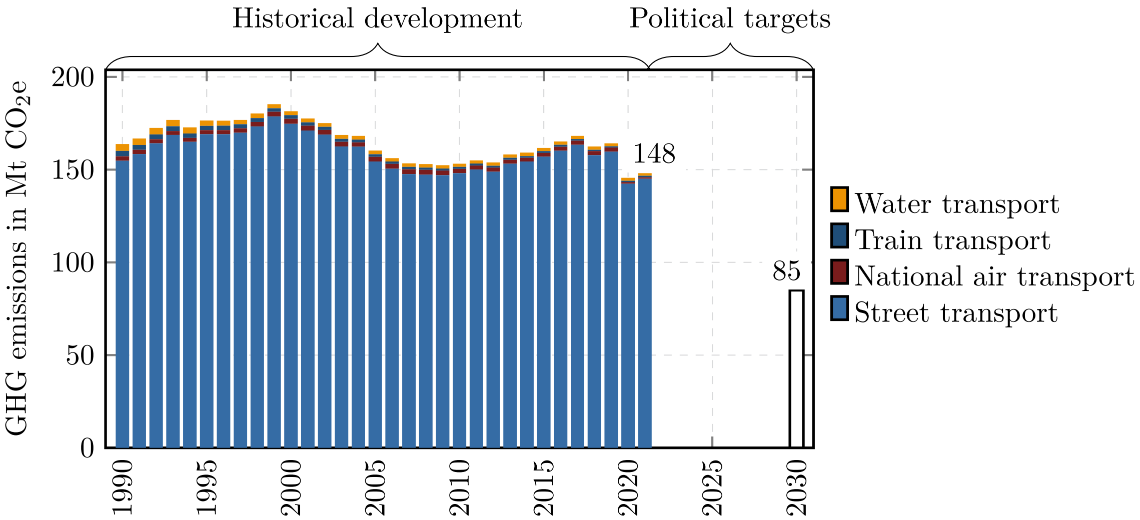


Figure 3.5: Historical development of GHG emissions in Germany [60] and political targets [68]

In 2021, the total transport emissions were 148 Mt CO$_2$e, which amounts to levels that are 2 Mt CO$_2$e higher than the year before and 18 Mt CO$_2$e lower than in 2019. The decrease between 2021 and 2020 was thought to be due to the COVID-19 pandemic containment measures that significantly reduced mobility [69]. However, emissions didn't increase significantly in 2021. Apart from this, although there has been a change in transport sector emissions over the last three decades, in 2021 emissions were just 18 Mt CO$_2$e lower than in 1990. In view of this, the German government's target of reducing emissions to 85 Mt CO$_2$e by 2030 is expected to be difficult to achieve. It should be noted that since the national emission targets only include domestic air traffic, international flights departing from Germany are not included here. [60]

As described in the previous section, the bulk of energy consumption is covered by oil-based fuels. As these have very similar emission factors, the distribution of GHG emissions is similar to that of energy consumption. In addition, in most emission balances and emission targets, emissions are accounted for according to the 'source principle'. This means that emissions are accounted for in the areas where they physically arise and thus no emissions arise from the use of electricity in the transport sector. An alternative accounting method is the 'cause principle'.

Here, emissions are allocated to the sectors that consume the energy. This approach was implemented in the so-called 'application-oriented emissions balance' by Pichlmaier et al. [70] whereby only CO_2 emissions and no other GHG emissions were considered. In this paper, the emissions from the provision of electricity, heat, and fuels are allocated to the final energy consumers. In 2016, 81 % of the 362 Mt CO_2 was attributable to the production of electricity in the supply sector and only 9 % was caused by the production of district heating and 10 % by the provision of fuels. Consequently, the increase in emissions in the transport sector was low at 12 %. This is in contrast to the other sectors of industry, private households, and services, which, due to their higher electricity consumption, recorded larger shares of additional emissions at 56 %, 47 %, and 63 % respectively. Nevertheless, with the expected developments in the field of drive systems in transport, the development of emissions in energy supply, especially electricity supply, is of great interest.

The energy sector has undergone the greatest change and the most significant reduction in GHG emissions (Figure 3.6). The most emission-intensive sector generated 427 Mt CO_2e in 1990. By 2020, emissions had fallen sharply to 221 Mt CO_2e [60]. The reduction is primarily due to the increasing use of renewable energy. In addition, rising prices in the EU Emission Trading System (EU ETS) combined with a low gas price in recent years have ensured that less electricity is produced from coal-fired power plants, and more electricity is produced using gas-fired power plants. The trends concerning the increasing share of renewable energies and the rising price of EU ETS certificates have continued in 2020 [71].

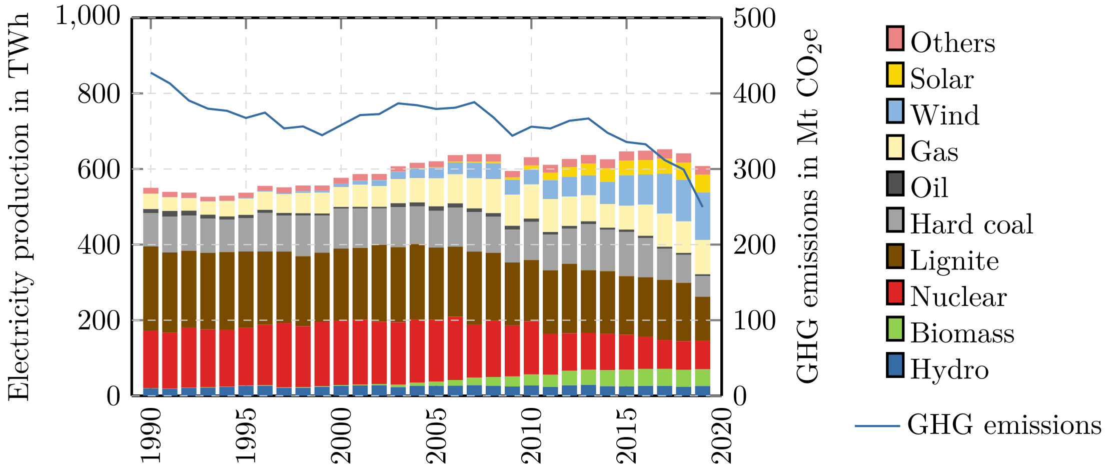


Figure 3.6: Historical composition of the sources of electricity generation [72] and the development of emissions in the energy sector [60]

3.2 Scenarios in the Literature

In preparation for the development of the scenarios to be evaluated in this thesis, scenarios from the literature are first analysed. Transport scenarios are examined first, whereby a distinction is made between the development of mobility and transport technologies. In addition, national and international scenarios of energy supply are examined.

3.2.1 Transport Scenarios

As outlined in Chapter 3.1.3, the target is to significantly reduce GHG emissions from transport. While there are ways to avoid, shift, and improve transport, in order for this to happen, a transformation of the sector is required, which includes both a change in mobility and an energy transition in transport. Mobility describes how much and with which modes of transport people or goods are transported and thus aims at exploiting the possibilities of avoiding and shifting. In addition, it is crucial to use energy with as few emissions as possible, which is to be achieved through the energy transition in transport and offers the possibility of improvement. In this chapter, a distinction is made between mobility and technology scenarios.

Mobility Scenarios The analysis of the mobility scenarios is based on a total of 10 scenarios from six different studies. Five of the studies are specifically German studies, while one of them is a Europe-wide study. The publication dates range from 2014 to 2021.

The project *Entwicklung der Energiemärkte - Energiereferenzprognose* [73] aimed to provide a forecast of probable energy developments up to the year 2030, including a further trend up to 2050. With 2014 as the year of publication, it is the oldest of the studies considered. In addition to the trend scenario, a target scenario was also developed, which has the same development in mobility. In the following, this scenario is referred to as *ERP*. In terms of transport performance, passenger transport will remain roughly the same until 2050, while freight transport will increase sharply due to rising economic growth. MIT is the most important mode of transport and will remain so in the future. More recent developments in mobility such as car sharing or autonomous driving are not part of the scenario, nor is a modal shift towards more public transport such as bus or rail. The increase in freight transport also largely takes place on the street due to the higher flexibility. [73]

In the project *Verkehrsentwicklung und Umwelt* [43], the DLR has been working intensively on the development of transport and the associated environmental impacts. The project, which ended in 2019, provides the only approach for the present analysis of scenarios coming from the perspective of transport research. With the scenarios *Referenz* (*DLR-Ref*), *Geregelter Ruck* (*DLR-GR*), and *Freies Spiel* (*DLR-FS*), three scenarios were created in this process that are based on different political framework conditions. In scenario DLR-Ref, current trends are continued and only moderate further interventions are made. On the roads, passenger traffic increases moderately and the volume of freight traffic rises significantly. A shift between different modes of transport barely takes place. In the DLR-GR scenario, political decisions are strongly influenced by the will to achieve climate protection goals. Under the conditions of a cooperative international environment, measures are taken that, for example, strengthen rail transport and make fuels more expensive. Thus, total passenger transport performance stagnates and there is a shift from MIT to public transport. Car sharing complements public transport in this scenario. Freight transport performance increases to the same extent as in the other scenarios, but most of it occurs in rail transport. The third scenario, DLR-FS, shows the global shift away from climate protection efforts in a highly competitive environment. For example, the tax rates of all energy sources are aligned and in the area of infrastructure, the focus is placed on roads and airports. In this context, passenger transport will increase by 9 % by 2040, with passenger car transport growing disproportionately. The increasing freight traffic will also be covered, to a large extent, by trucks. In this scenario, public transport decreases, which is not least due to the absence of innovative complementary services such as car sharing. [43]

In 2019, the UBA published the study *RESCUE* [13], in which six scenarios were used to investigate how climate neutrality can be achieved in Germany by 2050. With regard to the mobility scenarios, there were three different ones: *GreenEe* (*UBA-GEe*), *GreenLate* (*UBA-GLa*), and *GreenSupreme* (*UBA-GSu*). While all aim for a complete GHG reduction by 2050, the scenarios differ with regard to the medium-term ambition level, final energy demand, raw material extraction, and material efficiency. In the family of scenarios from UBA, UBA-GEe represents the baseline scenario. It refers to forecasts of transport development until 2030 and prescribes an ambitious implementation of climate protection measures. This leads to a corresponding avoidance and shift of traffic to lower-emission modes of transport. In comparison, the medium-term climate protection ambitions are lower in the UBA-GLa scenario. In addition, the energy demand and the raw material demand are higher in the whole UBA-GLa scenario. The most ambitious scenario up to 2030 is the UBA-GSu. Compared to the other two, fewer resources are needed and a stronger change in people's behaviour is assumed. The corresponding developments are also reflected in the transport performances. It should be mentioned at this point that the changes in transport performance in the scenarios were related to the value in 2010. Since the transport performance in freight transport, in particular, rose sharply between 2010 and 2018 [22], the transport performance in the UBA scenarios is significantly lower than in the scenarios of the other studies (see Figure 3.7). [13]

The study *Klimaneutrales Deutschland 2045* [10] is the most recent study among the mobility scenarios considered. Commissioned by Agora Energiewende, the study was published in 2021 and is based on the predecessor study *Klimaneutrales Deutschland 2050* [74]. It aims to provide an 'economically viable path' for Germany to be climate neutral by 2045 [10]. The study (hereafter referred to as *KD2045*) presents a mobility scenario that is intended to contribute to achieving climate targets. Similar to other scenarios, the total transport demand for passenger transport remains approximately the same, while freight transport increases. The share of MIT in passenger transport decreases, which is achieved through increasing multimodality supported by car sharing, ride pooling, and autonomous driving.

Accordingly, the use of public transport increases and freight transport also increases in all sectors with rail freight transport experiencing the largest growth. [10]

The *TREMOD* (Transport Emission Model) is used for emissions reporting in the NIR and thus represents one of the most important transport models in Germany. The current report [22] on the model also includes a trend scenario up to 2050. This scenario includes the continuation of current political and socio-economic framework conditions and, in particular, the development of technical parameters such as vehicle utilisation, vehicle classes, and stock and mileage shares of different modes of transport. Similar to other studies, an increase in passenger transport performance is assumed until 2030. After 2030, transport performance stagnates and from 2040 onwards it decreases moderately. The modal split road-rail remains the same. In freight transport, a strong increase is assumed, which decreases slightly after 2030. The increase in the volume of rail transport is slightly higher than that of road transport. [22]

The *EU Reference Scenario 2020* (*EU-Ref*) [75] is the only European mobility scenario in this evaluation due to the fact that it is the only scenario in the European context in which the data is provided in a sufficiently small granularity (national domestic transport performance). The study was commissioned by the European Commission and carried out under the direction of E3Modelling which is part of the National Technical University of Athens. The central model was the PRIMES model. With regard to the transport performance, an increase is assumed for both passenger and freight transport due to economic growth. However, in this study, it is passenger transport by rail and freight transport by road that increases more strongly. [75]

In summary, the transport services are plotted in Figure 3.7. They are intended to be an indicator of the trends in the individual scenarios and contain the MIT for passenger transport and public transport by rail and road. For freight transport, the representation includes the modes of transport by road, rail, and inland navigation. There is a significant difference in freight transport performance if the UBA scenarios are compared with the others. This clear difference is not yet apparent in passenger transport, at least until 2030, and it is even the case that in the UBA-GLa scenario the highest values occur in 2030. However, in further developments, the transport performances of the UBA scenarios decrease significantly, especially that of UBA-GSu. Other scenarios also assume a decline in transport performance in the years 2030 to 2050. Only the scenarios EU-Ref and TREMOD assume that transport performance in 2050 will be above the extrapolated trend of the last 10 years. As already mentioned, the clear differences between the UBA scenarios and the other scenarios with regard to freight transport are due to the fact that a moderate increase in transport performance since 2010 is assumed. However, this neglects the fact that the increase up to 2018 was significantly higher. Apart from that, the other scenarios are very similar in their development. The increasing trend of the last 10 years is continued until 2030 and partly until 2040. Afterwards, the increase in all scenarios flattens out, i.e. it is assumed that saturation will occur.

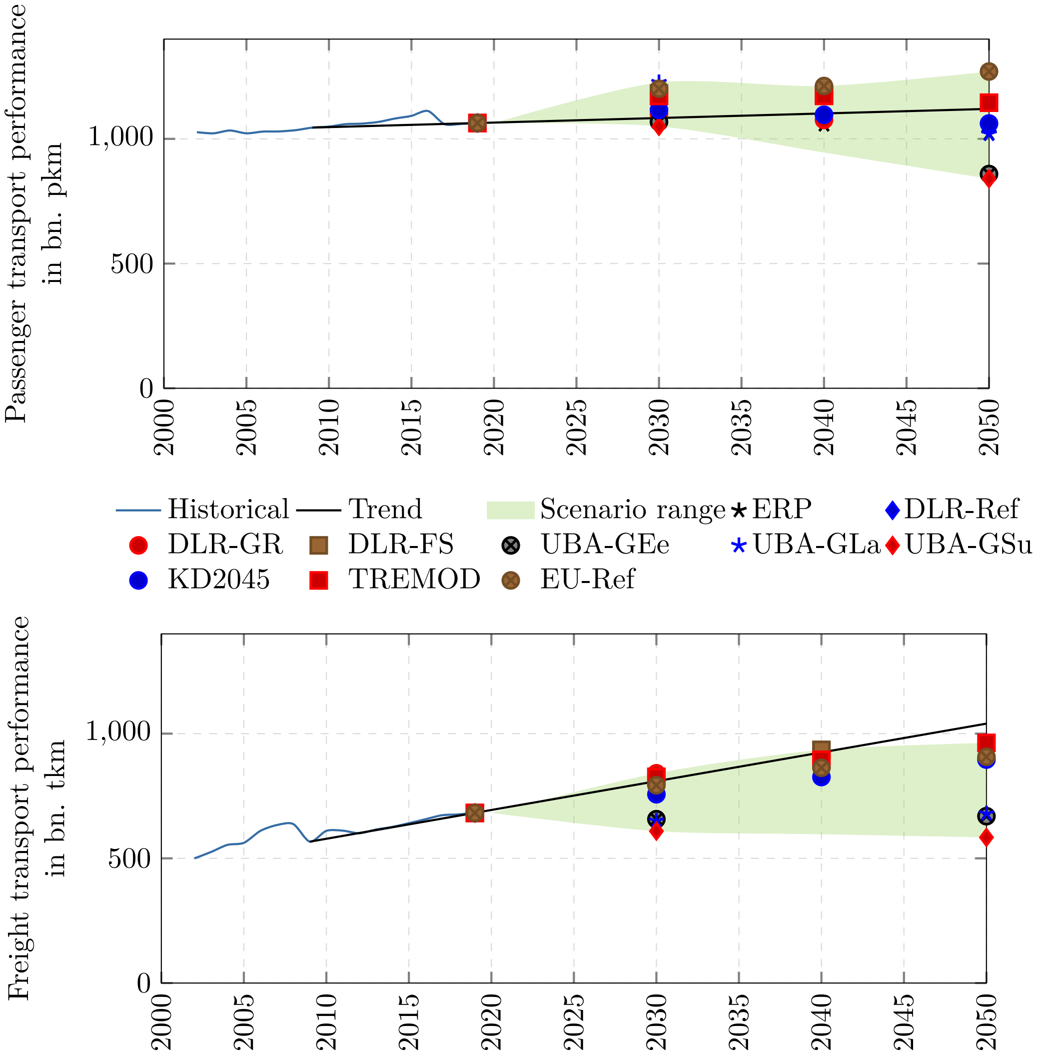


Figure 3.7: Range of passenger and freight transport performance in the scenarios considered up to 2050 [10, 13, 22, 43, 73, 75]

Technology Scenarios For the meta study of technology developments, 11 scenarios from six different studies are examined whereby particular attention is paid to developments in road transport. In the other transport areas, only small changes in technologies, if any, are to be expected. The shift away from fossil fuels will primarily take place through the switch to renewable fuels.

The previously mentioned study *Klimaneutrales Deutschland (KD2045)* by Agora Energiewende is also included in the meta study of technology scenarios [10]. The clear goal of climate neutrality in 2045 is implemented on the technology side through a focus on electrification. There will be a complete switch to BEVs and FCEVs in all road transport sectors by 2050, with hydrogen only being used to a lesser extent in the commercial vehicle sector. It is important to mention that the fleet composition was exogenously specified in the modelling, which means that the model itself does not determine the cost-optimal fleet composition on the basis of techno-economic data. [10]

In October 2021, the German Energy Agency (dena) published their dena Leitstudie Aufbruch Klimaneutralität (KN100) [11] study. The scenario described therein achieves GHG neutrality by 2045. In the transport sector, a mix of technologies is used. In the area of cars, the focus is mainly on BEVs, with a significant reduction of the total vehicle fleet to 36 million vehicles, 30 million of which have a purely electric drive. In the HDV segment and especially in the area of semi-trailer trucks, larger quantities of hydrogen are used. In all areas of road transport, however, small quantities of hydrocarbons will still be needed in 2050, which will accordingly have to be produced from non-fossil sources. The fleet modelling is carried out model-exogenously with the help of a new registration model. [11]

The most recent study considered is the *BMWi Langfristszenarien* [12]. These scenarios were developed by a broad project consortium, with the transport modelling being performed by *Fraunhofer ISI*. In the course of this study, among other things, three extreme worlds were identified that aim for CO_2 neutrality by 2050. These three worlds each focus on electricity (*LFS-El*), hydrogen (*LFS-H2*), or synthetic fuels (*LFS-PtX*). In this case, the fleet modelling happens endogenously which means that a cost-optimal development of the drive technologies takes place on the basis of the set techno-economic data. In the LFS-El scenario, almost only electricity or synthetic fuels are used over the entire period. However, although large shares of cars and LDVs are electrified by 2050, carbon-based fuels dominate the HDV sector. The development for LFS-H2 is very similar. However, a comparatively small share of FCEVs will be used in the passenger car sector and the share of synthetic fuels in the HDV sector will be replaced by hydrogen. In the LFS-PtX scenario, it should be emphasised that only 30 % of vehicles in the passenger car sector will be electrified by 2050. [12]

The project *eXtremOS* was carried out by the FfE Munich and was completed in 2021 [8]. This is a European energy system study that also adopts different national developments of the consumption sectors. Since the focus of this dissertation is on Germany, this scenario is referred to as *XOS-DE* in the following. The scenario is to be classified as a climate protection scenario in which the transport sector undergoes the fastest change of all scenarios. Especially in the LDVs sector, the type of propulsion system changes very quickly as 79 % are electric by 2030, and complete electrification is implemented by 2040. In addition to electrification, hydrogen vehicles will also be used in passenger cars and HDVs. By 2050, the change will be complete in all sectors and hydrocarbons will no longer be used in road transport. [8]

The study *Wege in eine ressourcenschonende Treibhausgasneutralität* by the UBA that was mentioned earlier also includes various technology scenarios [13]. Consistent with the previous analysis of transport performance, the scenarios *UBA-GEe*, *UBA-GLa*, and *UBA-GSu* are also included here. In each of the three scenarios, only BEVs and internal combustion engine vehicles (ICEVs) are used for road transport and hydrogen plays no role. Compared to the other scenario studies, however, a shift from ICEVs to BEVs is very slow in all three areas.

The UBA-GEe scenario represents the baseline scenario in the UBA scenarios. In UBA-GLa, the change is carried out much more slowly than in UBA-GEe, which means that even in 2050, 77 % of vehicles in the HDV segment will still be powered by internal combustion engines. The progressive scenario UBA-GSu has a significantly faster development towards BEVs than the other two scenarios, especially in the years between 2030 and 2040. This ensures that in UBA-GSu, 47 % of the vehicle stock in the passenger car segment is electric, compared to 34 % in UBA-GEe and 23 % in UBA-GLa. [13]

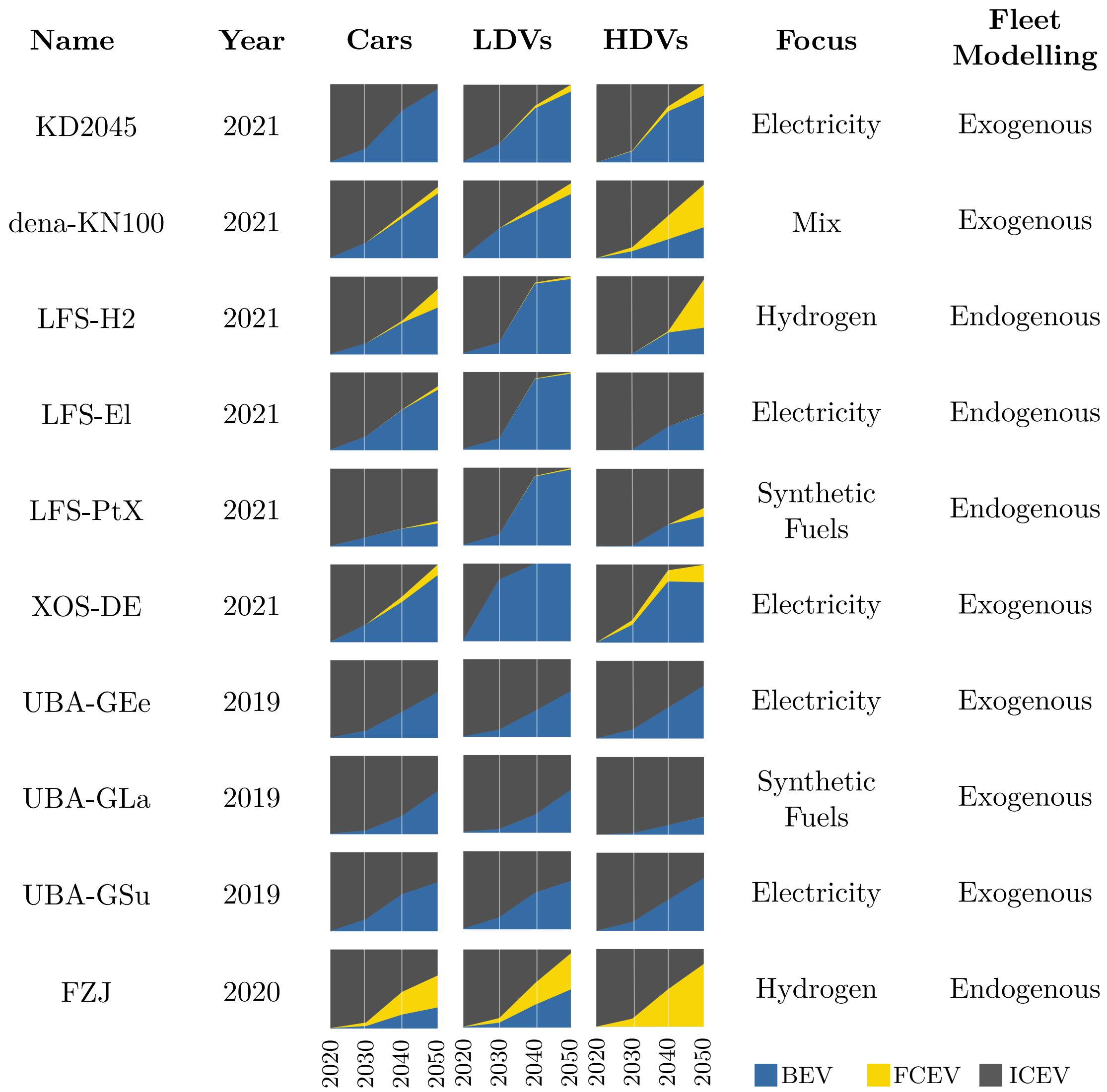
In 2020, the Forschungszentrum Jülich published the study *Wege für die Energiewende*. This study contained two scenarios, one with an 80 % and one with a 95 % reduction in CO_2 emissions by 2050. The 95 % scenario, which will be referred to as *FZJ* in the following, is part of the present analysis. It should first be mentioned that, in this case, the modelling is model-endogenous and thus the techno-economic parameters are decisive for the choice of the propulsion technologies used. Compared to the other scenarios considered, the high proportion of FCEVs is striking. Already in 2030, the shares of FCEVs are greater than or equal to those of BEVs in all three segments of road transport. In the further course up to the year 2050, the shares in the car segment increase more strongly for FCEVs than for BEVs. No BEVs are used in the HDV segment and only in the LDV segment is the share of BEVs, at 49 %, slightly higher than that of FCEVs, at 46 %. The shares of the remaining ICEVs in the transport system in 2050 are low compared to other studies.

Figure 3.8 shows the resulting overview of the scenarios considered, their publication year, and the fleet developments of cars, LDVs and HDVs. It also shows which GHG reduction measures are focused on and the type of fleet modelling.

While all scenarios are target scenarios that achieve CO_2 neutrality by 2050 at the latest, the results are nevertheless very diverse. Although the transport sector in all scenarios is undergoing a fundamental change in terms of the technologies used and therefore alternative drives are increasingly entering the system, the scenarios also differ in terms of their development. In 9 of the 11 scenarios considered, ICEVs are still in the passenger car fleet in 2050. It is striking that in many of the scenarios the shift towards alternative powertrains is faster for LDVs than for passenger cars. This is due to the lower required and plannable ranges as well as the shorter lifetimes in the LDV sector [9]. The transformation is slowest in the HDV segment. Among other things, this is also connected to the fact that the change is initiated later.

3.2.2 Energy Scenarios

Energy scenarios show possible images of the future. It is always important to note that scenarios are not intended to represent a forecast, but rather a potential design of the energy systems. These are subsequently used to describe the interactions within the systems. In the following explanations, no meta analysis of all existing scenarios in the literature is made.



Name	Year	Focus	Fleet Modelling
KD2045	2021	Electricity	Exogenous
dena-KN100	2021	Mix	Exogenous
LFS-H2	2021	Hydrogen	Endogenous
LFS-El	2021	Electricity	Endogenous
LFS-PtX	2021	Synthetic Fuels	Endogenous
XOS-DE	2021	Electricity	Exogenous
UBA-GEe	2019	Electricity	Exogenous
UBA-GLa	2019	Synthetic Fuels	Exogenous
UBA-GSu	2019	Electricity	Exogenous
FZJ	2020	Hydrogen	Endogenous

Figure 3.8: Analysis of the fleet compositions of cars, LDVs, and HDVs in different scenarios from the literature [8, 10–14]

Instead, individual scenarios are discussed by means of examples in order to gain an indication of which components are important in the vision of energy supply.

German Energy Scenarios The previously mentioned studies *KN100* [11], *KD2045* [10], and *Klimapfade 2.0 (KP)* [76] are used to illustrate the energy system of the future in Germany. All three studies were published in the second half of 2021 and, in accordance with the Climate Protection Act 2021 [68], describe a path in which GHG neutrality is achieved in 2045. Additionally to the goal for 2045, the studies achieve the climate protection targets of the individual sectors by 2030 as a further boundary condition (also see Chapter 3.1.3). These require rapid transformation. The central component of the transformation in energy supply is the expansion of renewable energies in Germany. In particular, the expansion of photovoltaic systems on roofs and on open sites as well as onshore and offshore wind energy systems is strongly emphasised in all studies. It must also be taken into account that the future demand for electricity, hydrogen, and Power-to-Liquid (PtL) fuels will increase. The summary of the key figures is shown in Figure 3.9.

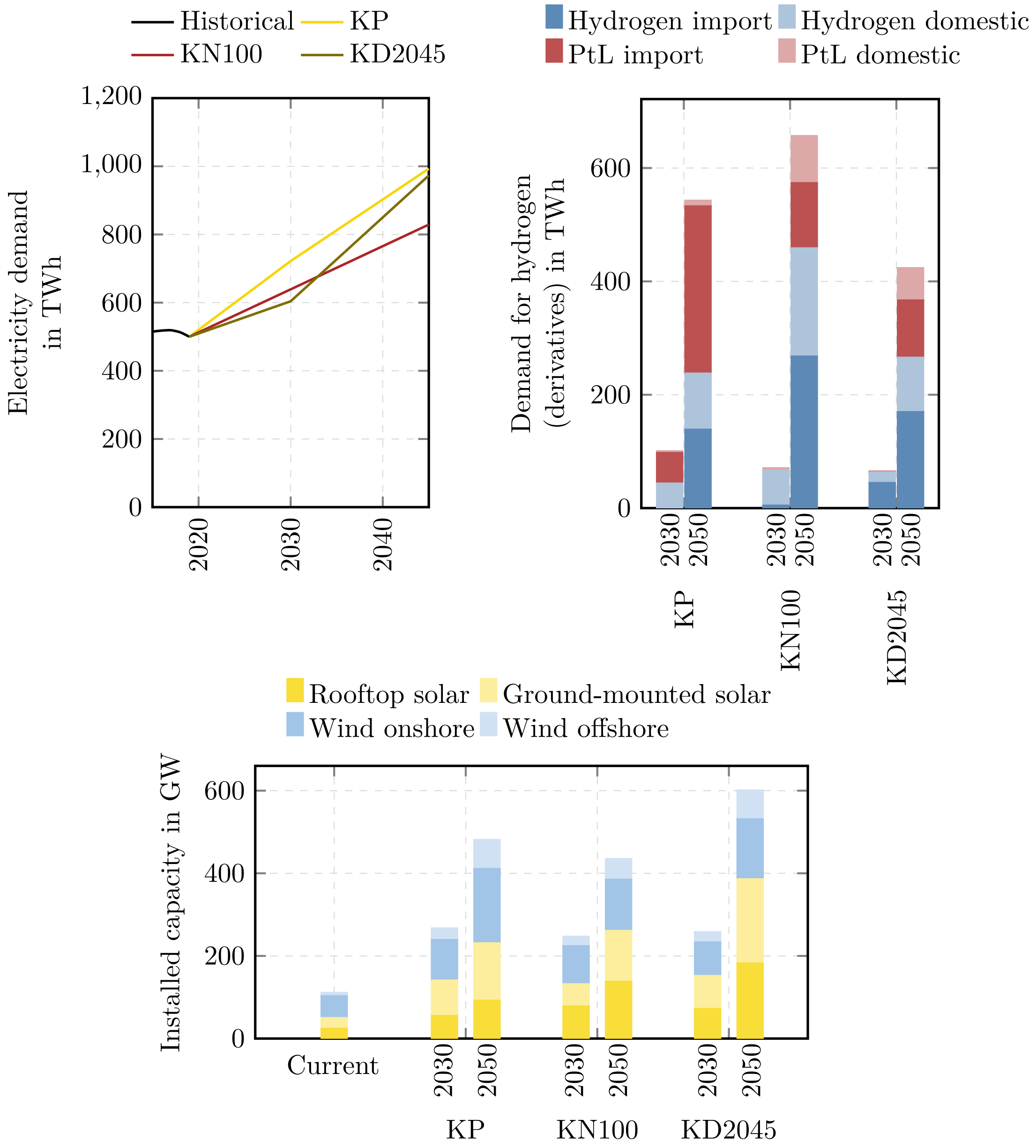


Figure 3.9: Developments of electricity (top left) and hydrogen derivatives demand (top right) and installed capacity of renewable energy generation technologies in the studies KP, KN100, and KD2045 [10, 11, 76]

The figures show that a multiplication of the installed capacity of solar and wind is needed to achieve the climate targets. According to the three studies, an increase of 135 % to 235 % is needed by 2030 for rooftop solar, 108 % to 231 % for ground-mounted solar, 53 % to 85 % for onshore wind, and 188 % to 250 % for offshore wind. The change becomes even clearer with a view to 2045. According to the three studies, the sum of the installed capacities from the four areas must be increased to between 395 % and 545 % of the current value. Even though the studies agree that a massive increase in the installed capacities of all energy sources is necessary, the distribution among the individual energy sources is not yet clear. For example, the KP study focuses on a stronger expansion of wind energy on land. On the other hand, the KD2045 study sees considerably larger shares in the area of solar energy, both on open sites and on roofs. The necessary expansion of renewable power generators is driven, on the one hand, by the restructuring of the energy system, which calls for the phase-out of nuclear and coal-fired power generation in the coming years. On the other hand, however, the demand for electricity is also rising due to the increasing levels of direct and indirect electrification of various areas in the energy application sectors. The electricity demand of the application sectors was 500 TWh in 2019 [77]. The three studies assume that this will increase by 21 % to 44 % by 2030 and by 66 % to 99 % by 2045. Thereby, indirect electrification is defined as the use of electricity-based molecules as energy carriers such as hydrogen and liquid hydrocarbons (PtL). The quantities of these two energy sources that are used is another characterisation feature of future energy scenarios. As shown in Figure 3.9, the demand in these areas is also increasing strongly. According to the German National Hydrogen Strategy [78], the current hydrogen demand amounts to roughly 55 TWh, which is mainly used for material production. Based on this, the studies assume an increase in demand of 43 TWh to 66 TWh by 2030 and 237 TWh to 458 TWh by 2045. In the long term, most of the hydrogen in all studies is to be imported. Until 2030, however, the two studies KN100 and KP assume that the hydrogen will essentially be produced in Germany. There is currently no demand in the PtL area and in KD2045 and KN100 the increase in demand up to 2030 is assumed to be correspondingly slow (1 TWh and 4 TWh respectively). An exception is KP, where demand is already assumed to be 57 TWh in 2030. This demand is almost exclusively covered by imports. Until 2045, the demand increases strongly in all studies and demand quantities of 158 TWh to 305 TWh are calculated. All in all, a uniform picture emerges with regard to the massive expansion of renewable energies and the rising demand for electricity, hydrogen, and PtL. Linked to this, in addition to domestic electricity production, are imports that are changing from conventional energy sources such as mineral oil to environmentally friendly gases and liquids. The associated change in the German energy supply can thus be classified as profound.

Global Energy Scenarios The classification of global energy scenarios can only take place in a very abstract form in the present work. To illustrate possible paths of future development, the IPCC uses the Representative Concentration Pathways (RCPs) which are projections for global GHG emissions and the associated radiative forcing. Table 3.2 shows the different pathways used. It should be mentioned here that in the framework of the Paris Agreement, 196 countries have committed themselves to reduce their GHG emissions in such a way that global warming is limited to well below 2 °C and preferably to below 1.5 °C relative to pre-industrial levels [79].

Table 3.2: Explanation of RCPs based on [80–82]

RCP	**Forcing**	**Temperature**	**Emission Trend**
1.9	1.9 W/m^2	~1.3 °C	Very strongly declining emissions
2.6	2.6 W/m^2	~1.8 °C	Strongly declining emissions
4.5	4.5 W/m^2	~2.7 °C	Slowly declining emissions
6.0	6.0 W/m^2	~3.3 °C	Stabilising emissions
8.5	8.5 W/m^2	~4.0 °C	Rising emissions

Combining the RCPs with the Shared Socioeconomic Pathway (SSP) results in a powerful framework for evaluating future pathways and possibilities for climate change mitigation. Thereby, the SSPs provide consistent sets of assumptions for the societal, technical, cultural, and economic developments until 2100 [82]. A list of the SSPs is shown in Table 3.3

Table 3.3: Summary of SSP based on [82]

SSP	**Description**	**Existing Challenges**
SSP1	Sustainability	Low challenges to mitigation and adaption
SSP2	Middle of the Road	Medium challenges to mitigation and adaption
SSP3	Regional Rivalry	High challenges to mitigation and adaption
SSP4	Inequality	Low challenges to mitigation, high challenges to adaption
SSP5	Fossil-fueled Development	High challenges to mitigation, low challenges to adaption

All pathways assume an increasing energy demand until 2070 whereby the demands in the scenarios SSP2, SSP3, and SSP5 continue to rise until 2100. The energy demand in SSP4 stagnates after 2070 and SSP1 assumes a decreasing demand after 2070. The main difference between the SSP1 and SSP4 scenarios is also that in SSP4 the developments contribute to even greater inequality and thus lower-income groups find it difficult to adapt to the new economic developments. In SSP2, progress is slowly being made to reach Sustainable Development Goals (SDPs) although ecological systems are nevertheless steadily degrading. SSP3 is characterised by a growing nationalism that increases competitiveness and reduces overall security. There is little international cooperation, which causes the economic development of poorer regions to be very slow. The SSP5 path assumes strongly growing markets where fossil resources are available in large quantities and are exploited continuously. This path displays confidence that innovations can solve potential social and environmental problems. In this context, the energy requirements are derived by means of so-called Integrated Assessment Models (IAMs). These generally describe the developments in energy use, land use, and emissions associated with the narratives from the scenarios. In their basic variant, all SSPs are above the trajectory of RCP 4.5. However, various emission reduction measures can ensure that lower radiating forces are achieved. For example, the basis of SSP2 leads to a forcing level of about 6 W/m^2 by 2050 at a mean carbon price within the given time period until 2100 of 0.38 $. If the price is increased to a mean value of 10.20 $, the radiating force decreases to an RCP 2.6 level. Current policies are estimated to lead to an increase in the global temperature by about 2.8 °C and therefore correspond to RCP 6.0. Additionally, current pledges in the context of the Nationally Determined Contributions (NDCs) would lead to an increase in the temperature by 2.2 °C [83]. Thus, the pledges comply with a pathway close to RCP 4.5.

In summary, the global pathways that are described represent a wide range of possible futures. Even with the Paris Agreement, a strict path does not exist in the form prescribed by the Climate Protection Act in Germany. While the global energy consumption will continue to rise in the period under consideration in this dissertation until 2050, to what extent and with which technologies this will be supplied remains unclear.

3.3 Development of Scenarios

In the following section, the compilation of the scenarios used for the evaluation in this dissertation is presented whereby a distinction is made between transport and energy scenarios. First, the transport scenarios are developed and explained before the framework assumptions are presented for the energy scenarios.

3.3.1 Transport Scenarios

Analogous to the discussion of the scenarios from the literature, the development of the transport scenario will first deal with mobility trends before the technological developments in the transport sector are explained. In both categories, two scenarios are developed, which are combined with each other in the following.

Mobility Scenarios Both mobility scenarios are based on the studies of Schlesinger et al. [73] and Seum et al. [43] in which the demographic development ensures that passenger transport performance will decline slightly by 2050. Although Schlesinger et al. [73] did not consider car sharing, it is already part of the transport system today and therefore it will be integrated according to its current extent. Unlike in the study of Schlesinger et al. [73], flights that take off from Germany are also integrated in addition to national air traffic. For freight transport, the scenario *Geregelter Ruck* from Seum et al. [43] is used. Here, a fundamental increase in freight transport takes place. In this dissertation, the focus is more on the methodological assessment and less on the diverse design of scenarios. For this reason, freight traffic develops in the same way in both scenarios. In the following, the common freight transport sector will be explained before the differences in the two scenarios with regard to passenger transport are shown. At this stage, it must be mentioned that the year 2020 is a scenario year and thus does not refer to the historical year. This scenario year is more similar to the real year 2019 than 2020, especially with regard to traffic performance. In 2020, transport collapsed worldwide due to the COVID-19 pandemic and thus also in Germany and therefore this year is not representative.

According to the study of Seum et al. [43], it is assumed that there will be an increase in freight transport performance due to an increasing national and international division of labour. The attractiveness of the flexibility of freight transport by road results in a trend towards more road transport. However, this is counteracted by regulations and subsidies on the part of rail transport, so that the ratios of the two modes of transport remain more or less the same. This can be seen in Table 3.4.

Table 3.4: Developments in freight transport in the mobility scenarios Trend and Multi in billion tkm based on Seum et al. [43] and complemented by Conrad et al. [9]

	LDV	MDV	HDV	Semi-trailer	Train	Vessel	Airplane	**Sum**
2020	56.8	29.1	50.3	343.2	150.4	55.5	8.9	**694.2**
2030	76.0	37.6	65.0	388.9	186.7	77.5	11.3	**843.1**
2040	94.2	43.1	73.5	424.7	204.2	79.2	14.2	**933.1**
2050	113.3	48.3	81.0	461.0	220.6	80.9	16.6	**1021.7**

While Seum et al. [43] only distinguished between road transport, rail transport, and inland waterways, road transport is further divided and aviation is added with the help of Conrad et al. [9]. For this purpose, all road freight transport is separated into LDV, MDV, HDV, and semi-trailer. This is done on current traffic performance for the status quo. The transport performance of LDVs is increasing more strongly than that of the remaining road vehicles which is due to the disproportionate increase in delivery traffic. HDV and semi-trailer were separated at this point, as they show very different characteristics. While both operate in the highest capacity range, semi-trailers are designed to travel long distances and thus the semi-trailer sector is the one that most closely competes with rail. In addition, air traffic statistics were used to derive freight traffic by air [62]. The prognosis for future development is based on the assumption that air freight traffic will increase in line with overall freight traffic [9].

The differences in the mobility scenarios only relate to passenger transport. The scenario *Trend* is intended to continue with regard to the promotion of multimodal transport concepts, but not to exceed it. The scenario *Multi*, on the other hand, pursues the goal of optimally using multimodal public transport infrastructure to the maximum extent by means of car sharing. The description of the scenarios stems from Pichlmaier and Gyetko [84], building on two former studies of Gyetko [57] and Gyetko and Pichlmaier [58]. The following is a summary of this work. The basic developments in passenger transport performance originate from Schlesinger et al. [73] and were revised in the course of Conrad et al. [9]. In the years between 2020 and 2050, total passenger transport decreases slightly. This is largely due to the decline in MIT. Nevertheless, this still accounts for the bulk of passenger transport performance until 2050. However, the share of MIT so far only included private cars and no sharing options. These have now been supplemented for both scenarios in such a way that conventional modes of transport are substituted according to their share in the total transport performance. On the one hand, this does justice to the fact that not only journeys by private car are substituted, but also public transport. On the other hand, the clear multimodal integration into the overall transport system is also reflected here.

For a quantification of the scenarios, descriptors are derived from the influences of the stakeholders' politics and municipalities, car sharing users, and car sharing providers. On the regulatory side, a law was passed in 2017 that provides the legal basis for the establishment of exclusive parking spaces [85]. Furthermore, car sharing vehicles can be exempted from parking fees [86]. While these developments have already been implemented in the Trend scenario it is assumed that the status quo will not be further expanded. Another incentive measure would be to subsidise car sharing. This could be implemented, for example, through a reduced value-added tax (VAT) rate of 7 %. This measure is not transposed in the scenario Trend, nor is the reduction of the attractiveness of private car use through, for example, an emissions-based car toll. In some regions, car sharing is financially supported by the respective municipalities [87]. This mostly happens in densely populated areas and only occasionally in rural areas. However, even in the Trend scenario, such support is limited to individual cases. An important factor in the development of car sharing is its integration into overall transport concepts which requires cooperation with transport alternatives. This can be implemented through joint mobility packages, tariff reductions, and the distribution of information through timetables or maps although the conservative Trend scenario assumes that this will not happen. The expansion of car sharing also depends on the actions of the car sharing providers with regard to the design of the offer and its communication. The latter is the task of marketing, which aims at acquiring customers as widely as possible. However, this task is insufficiently addressed, which is reflected in the customers' insufficient level of knowledge about offers [88]. Thus, except for the increasing number of users due to age cohort effects, no further user groups are addressed in this scenario. According to surveys of car sharing users, the high proportion of BEV in the car sharing fleet is a key attractiveness factor [89, 90]. This is especially true for young people [91]. In the future, the share of electric vehicles in the car sharing fleet is also assumed to be higher than in the private fleet. As this is independent of the mobility scenario, this issue also applies to the Trend scenario. A final point where car sharing companies come in is in the use of digital services for reservation, localisation, billing, and information presentation [92]. This has a direct impact on the barrier to use due to the high planning effort [93]. Here, too, a stronger embedding in other local mobility service providers leads to more convenience although it is not assumed that this will be pushed beyond the current state in the conservative scenario. Finally, the customer as a stakeholder is responsible for which means of transport they choose. This decision is made on the basis of convenience, availability, speed, cost, reliability, flexibility, and ease of use [92]. The subjective perception of whether these factors are met can be influenced by marketing initiatives [94]. This does not happen in the present conservative scenario. The same applies to a fundamental change in values in society. This change in values could, among other things, lead to a stronger connection to the sharing economy and increase the perceived attractiveness of car sharing. Figure 3.10 summarises all influencing factors and the responsible stakeholders in the Trend scenario. [57]

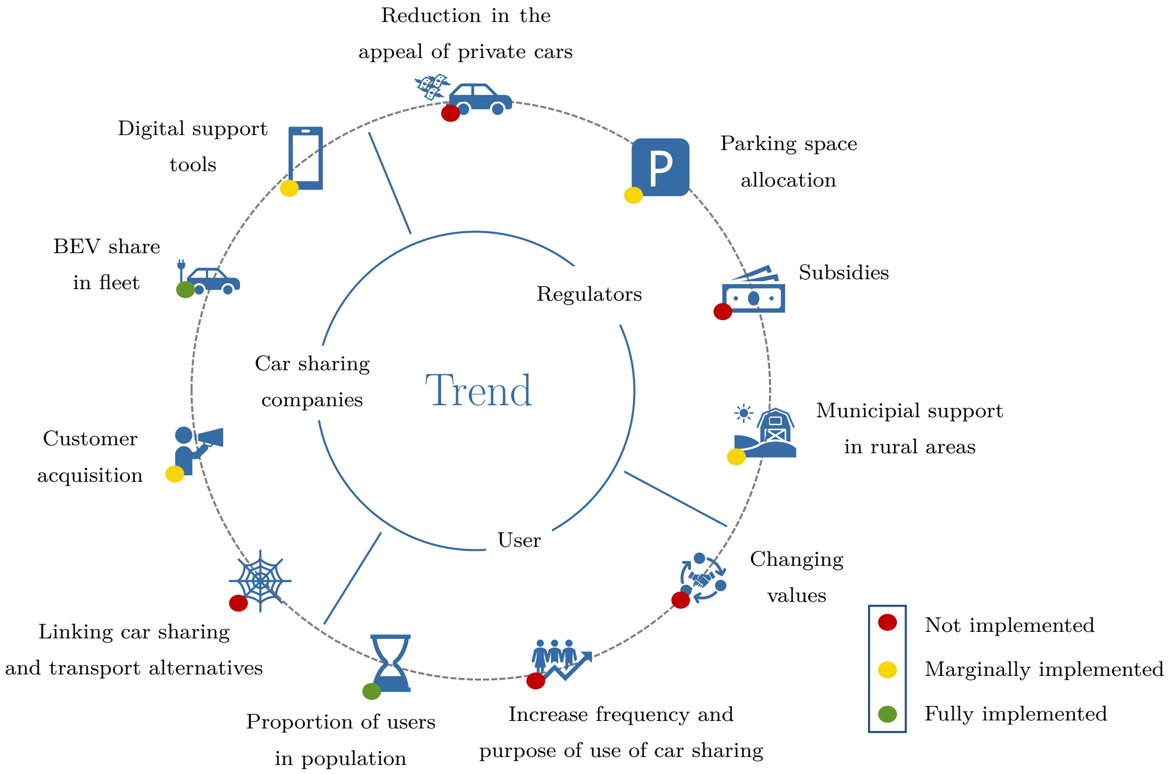


Figure 3.10: Qualitative influencing factors and responsible stakeholders for the development of the mobility scenario Trend based on Pichlmaier et al. [84] and Gyetko [57]

In the multimodal scenario Multi, measures are taken by the regulators to further strengthen car sharing, and thus further potential is developed by setting up car sharing stations in public transport areas. This requires an amendment of the Road Traffic Regulations and the Road Traffic Act [95]. Furthermore, the VAT will be reduced to 7 % in line with public transport. However, no measures are taken to reduce the attractiveness of using private cars. Car sharing services are dependent on a minimum population density and public transport infrastructure. Accordingly, the operation of car sharing in rural areas is difficult and would only be viable with municipal support even in the long term. As this is not considered a realistic option, no further measures for change in rural areas are implemented in the Multi scenario either. However, the scenario assumes intensive cooperation between car sharing operators and providers of transport alternatives such as public transport for which mobility points are developed that promote multimodal behaviour of the users by providing a diversified transport offer [88]. This has a direct impact on the barriers of planning effort and low flexibility. In addition, joint ticketing is being strengthened, which means that, for example, the sale of public transport tickets can be handled by car sharing providers [88]. Tariff linking in the form of mobility packages improves cost transparency and encourages multimodal transport behaviour [88]. Thus, the cooperation between car sharing and public transport takes on a key function in the Multi scenario. This also becomes clear in the area of customer acquisition as a joined distribution of information ensures that new customer groups are accessed [88]. This is supported by digital support tools such as applications that enable the live display of travel information from several transport providers and thus increase the attractiveness of multimodal use. The Multi scenario is also strengthened by a fundamental change in the values of potential users. An important factor here is a value adaptation of the sharing economy, which refers to using instead of owning and to sustainability [96]. This is already visible in younger generations today and will be further expanded by the age cohort effect [97]. A high affinity for multimodal use is also apparent in this scenario. Finally, the change in values also has an effect on the high level of openness towards BEV. The summary of the qualitative drivers and relevant stakeholders for the Multi scenario is shown in Figure 3.11. [57]

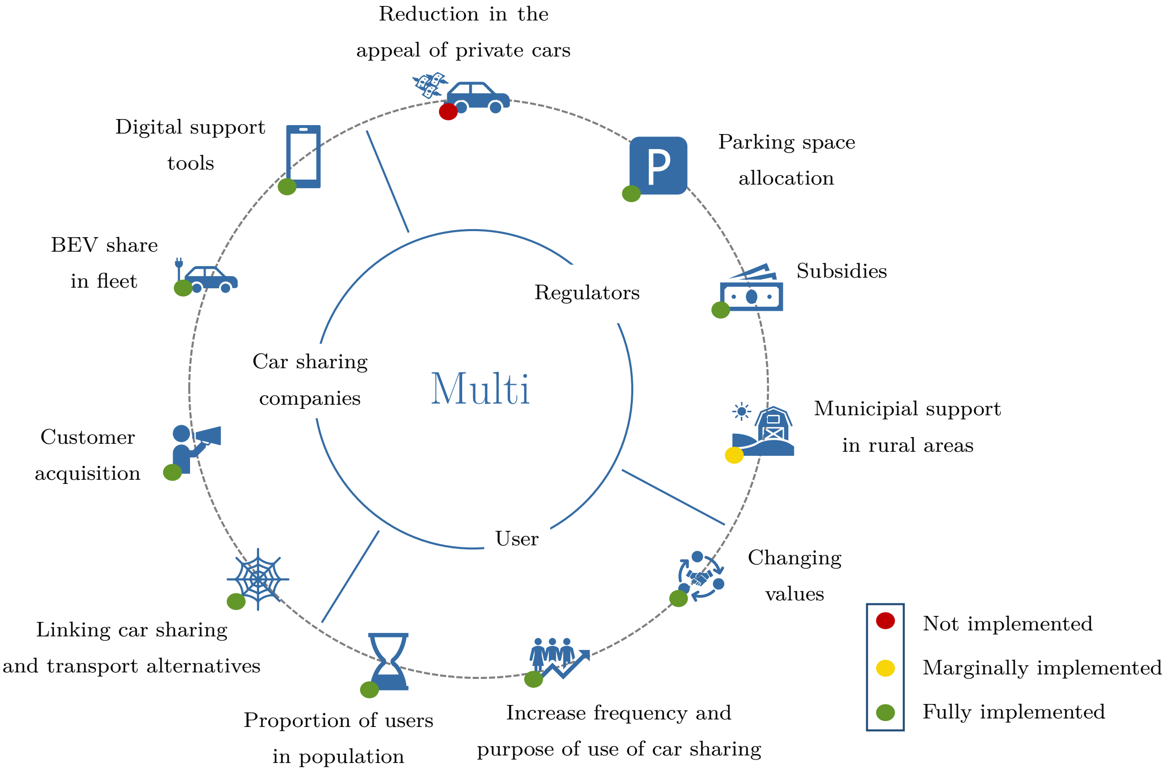


Figure 3.11: Qualitative influencing factors and responsible stakeholders for the development of the mobility scenario Multi based on Pichlmaier et al. [84] and Gyetko [57]

In order to be able to conclude quantitative values on the basis of the qualitative descriptions, the car sharing users were divided in the course of the study by Gyetko [57] into the respective region types in which they live and the car sharing service they use. The region types distinguish between metropolis, regiopolis, medium-sized city, and rural area. Depending on the age of potential users and their affiliation to a certain region type, their affinity to multimodality is determined [40, 86]. For younger persons, it is assumed that the proportion of multimodal persons will be higher in 2020. As a result, the number of users in the region is lower. Over the supporting years of the scenario, the multimodality of older users thus also increases. This results in a user potential per region type. SB and FF car sharing are differently suited for different types of regions and users and thus a distinction must be made at this point. For example, the share of users of FF services is higher in metropolitan areas than in regiopolitan regions [98]. Based on the user potential and the availability of services in the different region types, modal splits are now developed for the different region types, which in turn can be combined to produce a modal split for the scenarios of transport in Germany. The result can be seen in Table 3.5.

Table 3.5: Developments in passenger transport in the mobility scenarios Trend and Multi in billion pkm based on Schlesinger et al. [73] and enhanced by Pichlmaier et al. [84]

		Private car	Shared car	Motorcycle	Bus	Train	Airplane	**Sum**
Trend	**2020**	930.5	1.1	18.8	64.8	115.8	134.7	**1,265.7**
	2030	861.8	7.5	17.1	75.6	111.3	141.2	**1,214.5**
	2040	821.7	11.4	16.1	76.5	120.2	141.2	**1,187.0**
	2050	781.6	15.6	15.1	75.4	130.2	137.1	**1,155.0**
Multi	**2020**	930.5	1.1	18.8	64.8	115.8	134.7	**1,265.7**
	2030	807.3	33.9	16.1	77.8	144.7	141.2	**1,220.9**
	2040	659.2	83.8	12.9	98.3	195.3	141.2	**1,190.7**
	2050	468.0	139.6	9.1	119.5	261.4	137.1	**1,134.6**

In the Trend scenario, car sharing reaches a very low share of 13.4 billion pkm in 2050. The Multi scenario, on the other hand, increases the transport performance of shared cars and the public transport modes bus and train enormously whereby the use of private cars and motorbikes decreases accordingly. In the car sharing shares summarised here, the majority is allocated to SB car sharing. In the Multi scenario, the share of SB car sharing is 10.2 % and that of FF car sharing is 2.1 %. It is important to again emphasise the increase in the transport performance of trains. With 261.4 billion pkm in the Multi scenario in 2050, it is twice as high as in the Trend scenario (99.2 billion pkm). Thus, the strongly multimodal character of Multi becomes clear once again.

Technology Scenarios The design of the two selected technology scenarios aims to show paths that are as divergent as possible. On the one hand, a scenario is described in the following that, in accordance with past history, will essentially continue to rely on the combustion of hydrocarbons in the future. This scenario is referred to as CoHC. On the other hand, a scenario is described in which large parts of the transport sector are electrified. This scenario is subsequently named Elec. As described in Chapter 4.1.1, the new registrations are needed for the parameterisation of the technology scenarios. These are outlined for the two scenarios.

The scenario CoHC is based on the *Trend* respectively *Start* scenario of the studies of Schlesinger et al. [73] and Conrad et al. [9]. It corresponds to a conservative development of the transport sector in which the internal combustion engine will continue to be the most important form of propulsion in road transport in the future. Only a small proportion of passenger car traffic will be electrified and truck traffic will continue to rely on diesel combustion until 2050. The number of cars using CNG increases and there will be no change in the drive systems in most other areas. It is assumed that further electrification of railway lines will not be pursued due to a lack of economic viability. Furthermore, no innovations take place in the propulsion systems of aircraft and ships either. For a defossilisation of the transport sector, the main assumption is that the corresponding quantities of synthetic fuels from renewable energies will be available in the future. Tables A.3, A.5, A.7, and A.9 in the Appendix show the full commissioning data of all vehicle types for this scenario.

The Elec scenario is based on the climate protection scenario of Conrad et al. [9]. In this scenario, strong electrification is implemented in all road transport starting from 2020 whereby the majority of vehicles will already be electrically powered in 2030. Without a ban on new cars with combustion engines, new registrations of diesel and petrol cars are reduced to zero by 2045. In 2050, only a small proportion of vehicles with combustion engines (PHEV, HEV, CNG) will be registered. By far the largest share of vehicles will be BEVs and the rest FCEVs. In the area of semi-trailer trucks, partial use is made of overhead catenary semi-trailers (OCSTs) and overhead lines are also further extended in rail transport. In areas where this does not make sense, the locomotives are electrified with batteries. In the inland navigation sector, the energy carrier hydrogen is gaining ground. However, the low replacement rates in this sector will continue to maintain diesel-powered ships in 2050 and aircraft will continue to be powered by jet fuel. The commissioning data for the Elec scenario are listed in Tables A.4, A.6, A.8, and A.10 in the Appendix.

In order to gain an understanding of the scenario, the development of new registrations of cars is shown in Figure 3.12 in which the plots display the sum of the different propulsion systems for all four segments of the car sector.

As previously mentioned, the number of new registrations of vehicles using CNG is increasing in CoHC. This, and the rise of (partly) electrified vehicles, ensures that the number of new registrations of petrol ICEV declines completely. However, the largest share of new registrations in 2050 in the scenario CoHC are still vehicles using diesel as a fuel. This contrasts with a strongly changing car sector in the Elec scenario. Especially in the years until 2035, the share of new registrations of BEV increases strongly. The new registration rate of BEVs is 4.7 % in 2020, 29.8 % in 2025, and 53.6 % in 2030. When compared to the historical values in 2020, the value of the scenario is too low. However, the dynamics of the scenario are very high and much more likely to correspond to the dynamics also seen in the new registrations of BEVs (also see Table 3.1). Furthermore, the share of new registrations of ICEV using diesel

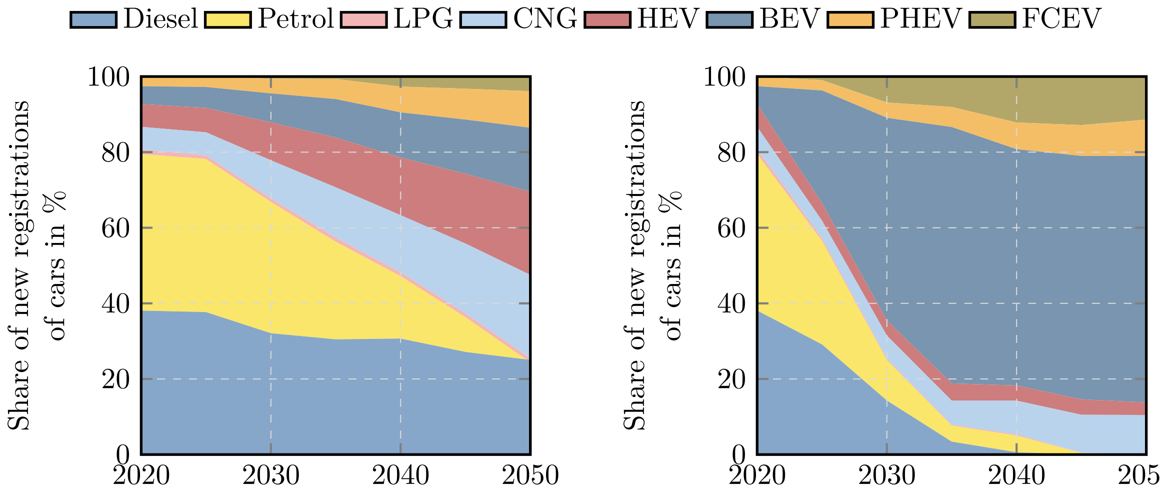


Figure 3.12: Shares of new registrations in all car segments in the technology scenario CoHC (left) and Elec (right)

or petrol decreases strongly and only the use of CNG in ICEVs increases slightly. There is also a use of hydrogen in FCEVs, especially in medium and upper class vehicles.

3.3.2 Energy Scenarios

For the development in the energy supply sector on the European and global level, the basis of already existing scenarios is initially used. This setting is underpinned with framework assumptions using quantitative values. These initially include values such as gross domestic product (GDP) and population development. The energy demands of the sectors industry, tertiary, and households are also derived from literature and listed in the following section. Since this dissertation focuses on transport, the other sectors will not be calculated as being model endogenous.

Developments in Europe The developments of the other consumption sectors (industry, household, tertiary) and energy supply are based on the solidEU scenario of the eXtremOS project [8]. In order to describe the general narrative of the scenario solidEU, the following section was taken directly from the study:

The scenario describes a sociopolitical setting characterized by cooperation and a stronger integration of the European Union, with a strengthened participatory democracy. Solidarity and the resulting participative governance are driven by the common understanding that climate change is anthropogenic and poses a serious threat to personal prosperity. This pioneers an ambitious climate policy, supported by the collective goal of deep greenhouse gas reduction at both governmental and societal levels. Consequently, the EU will create a solid national policy framework. The countries which currently have more organized national policies/goals will adapt these to the EU framework. There will be regulations on trade of various resources

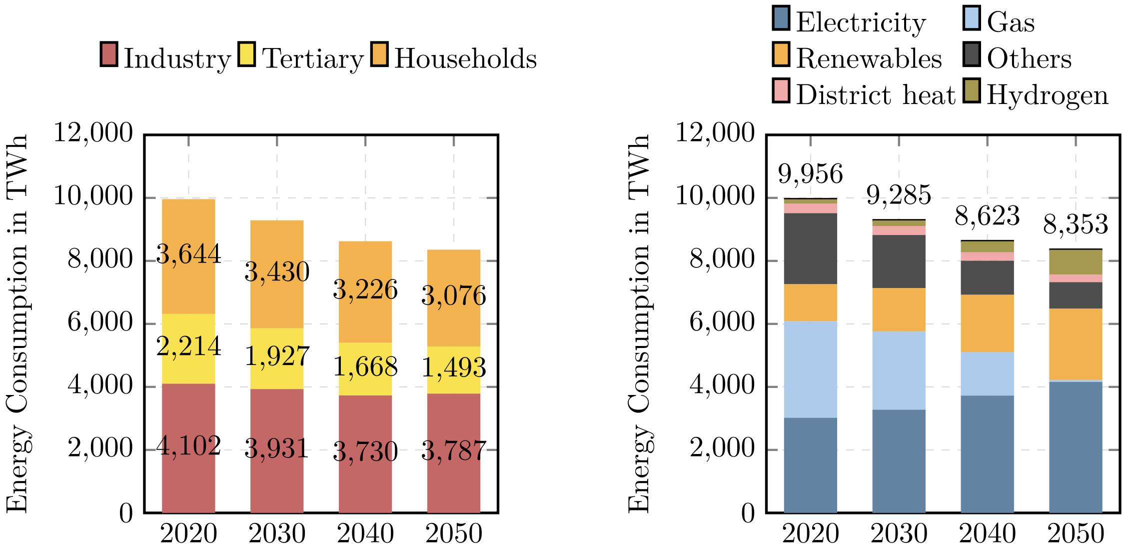


Figure 3.13: Energy consumption of the industry, the tertiary, and the private households sector in the scenario solidEU of the project eXtremOS [8] broken down by sector (left) and energy source (right)

to implement environmental standards, promote the use of locally available resources, protect sensitive ecosystems, and avoid social conflicts. Intensification of renewables will be promoted by funding research and development as well as technology infrastructure. Moreover, society will work in solidarity for climate protection, triggering lifestyle changes via increased climate awareness. Therefore, people become conscious about their consumption, switching to products with a low carbon footprint. Hence, there will be a new economic order supporting circular economies and reducing consumption of primary resources. Economic growth continues or slows depending on the country. Furthermore, integration of variable renewable energy sources between EU member states is supported with demand-side management. [8, p. 12]

On the basis of this narrative, the final energy sectors were developed. For the industrial, tertiary, and private household sectors, the resulting energy consumption in Europe is shown in Figure 3.13.

In line with the targets in the scenario, the energy consumption of all three sectors decreases. This is, among other things, due to the fact that many areas become electrified and the corresponding applications are generally more efficient. Although this increases the demand for electricity, the demand for gas and other energy sources (mostly carbon-containing, liquid energy sources) falls sharply. In the years after 2030, there is also an increase in the demand for hydrogen which is predominantly induced by the industry sector.

The narrative described above also causes fundamental changes in the supply sector. Adding the transport sector of the solidEU scenario to the demands described above results in an energy demand of 9,685 TWh to be met in 2050. This corresponds to a reduction of 31 % compared to 2020. The European cap for GHG emissions of 6 % compared to 1990 ensures an expansion of the installed capacity of renewable energy to 3.154 GW. This corresponds to a multiplication of the capacity of 2020 by a factor of 7.6. The electricity to be generated from this amounts to 6.533 TWh. In the area of conventional energy generation, the installed capacities of flexible gas-fired power plants are increasing strongly. In addition, nuclear power plants are still on the grid in 2050 in countries that are not planning a phase-out. A strong European grid provides the necessary flexibility in the system. The production of hydrogen by means of electrolysis is also greatly expanded and European hydrogen production will increase to 1.085 TWh. In 2050, steam reforming will no longer be used. In addition to transport and industry, in SolidEU hydrogen is used as a seasonal electricity storage. In the area of liquid hydrocarbons, demand is declining sharply from 5,177 TWh in 2020 to 387 TWh in 2050 whereby 71 % of the remaining energy in 2050 is imported and the remaining quantities are produced within Europe. However, it should be noted at this point that significant quantities of the current demand for liquid hydrocarbons come from the transport sector. Since this sector is excluded and recalculated in this dissertation, the figures for liquid hydrocarbons in the solidEU scenario are only intended as a classification. In a diminished manner, this analogously applies to the other energy sources.

Global Developments For global developments, reference is made to the SSPs that was already mentioned in Chapter 3.2.2. SSP2 serves as the basis for the two developments described in this dissertation [99]. The pathway is also called *'Middle of the road'*. O'Neill et al. described the path as follows:

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing *moderate challenges to mitigation and adaptation, but with significant heterogeneities across and within countries.* [99, p. 5]

As explained by Riahi et al. [82], the SSPs' narratives are then used to project GDP and population in order to hand it over to the IAM teams. Five modelling teams subsequently derived 105 scenarios which contain, among other things, projections for final energy demand and how this will be supplied. Further development of emissions and the associated global warming are shown. For this dissertation, the calculations for SSP2-2.6 and SSP2-4.5 of the REMIND model are used [100]. Figure 3.14 displays some key parameters for understanding the scenarios.

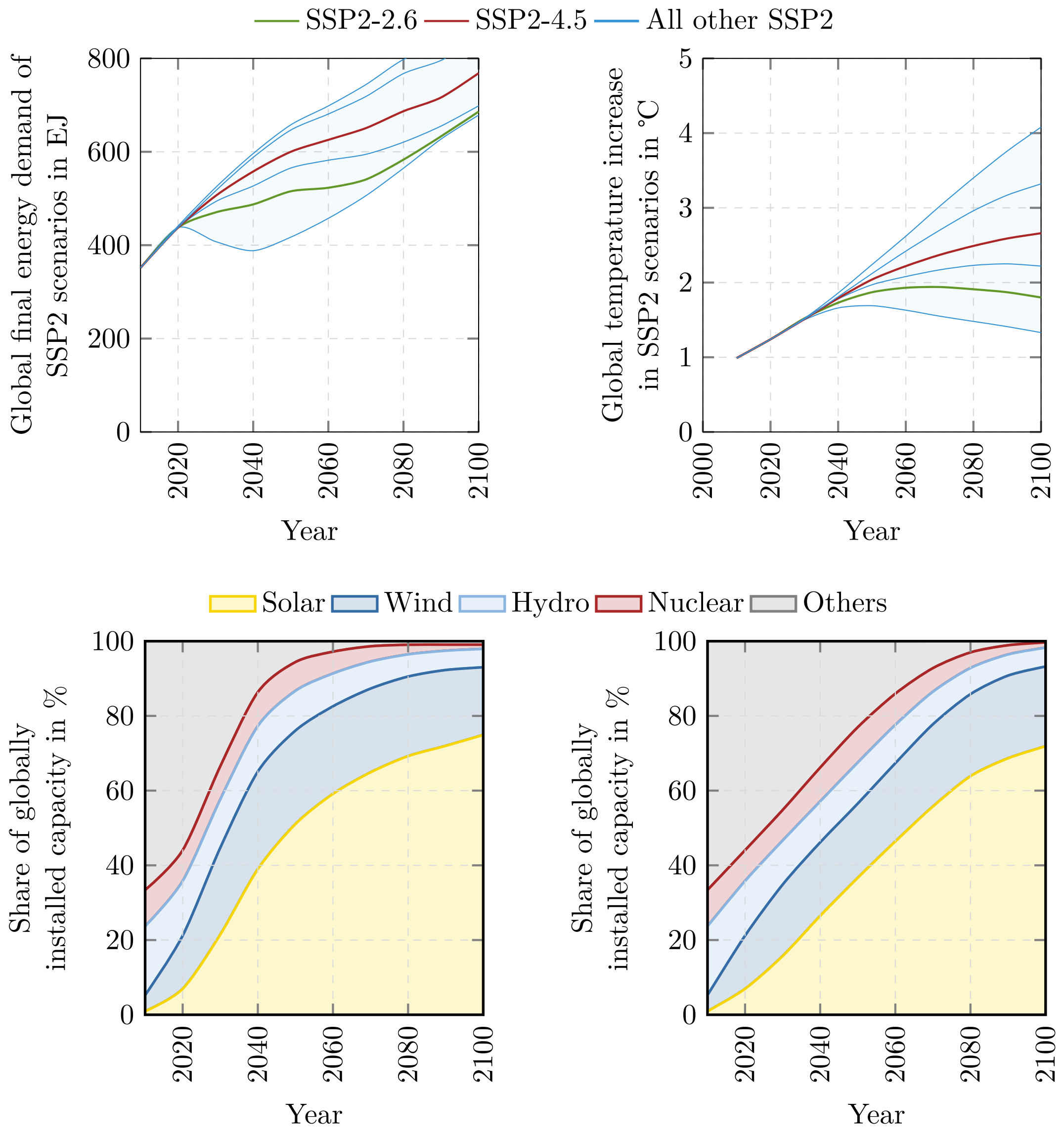


Figure 3.14: Global final energy demand (top left) and mean temperature increase relative to pre-industrial levels (top right) in the SSP2 scenarios; development of installed capacities of electricity generation technologies in the scenarios SSP2-2.6 (bottom left) and SSP2-4.5 (bottom right); own illustrations based on Riahi et al. [82]

In all SSP2 scenarios, the final energy consumption increases until 2100. However, the increase in SSP2-2.6 is at a lower level than that in SSP2-4.5. The two scenarios increase the temperature by about 1.8 °C and 2.7 °C, respectively, in the long term. In SSP2-2.6, even higher temperatures are reached in between, but these temperatures drop again towards the end of the century. A significant difference in the two scenarios arises concerning the way in which electricity is generated. In SSP2-2.6, more than 50 % of the electricity is already generated from solar, wind, and hydropower by 2030. In SSP2-4.5, this is only the case 10 years later. It is precisely in the years before 2050 that a rapid switch to renewable energy sources succeeds, which ultimately also leads to a significantly lower rise in temperature. These scenarios initially form the basis and are then adapted with the help of the result of the energy system modelling for the European region.

3.4 Preliminary Summary

In this chapter, the transport sector was explained concerning its structure and past developments, and possible future trends were discussed. While the transport sector has not undergone major changes in the past, the targets set for 2030 and 2045 are very ambitious. If they are achieved, this would ensure a fundamental change in the transport sector. As a basis for the development of own scenarios for further evaluation, the literature on transport sector scenarios was reviewed with the help of 10 mobility scenarios and 10 technology scenarios. Furthermore, current studies in the field of the energy sector were shown, which take up current trends.

The scenarios for further assessment are also separated into mobility and technology scenarios. The mobility scenario Trend continues currently visible trends in mobility. This is contrasted with the Multi scenario, which assumes a strong increase in multimodal transport use. The technology scenarios are named CoHC and Elec. CoHC is an acronym for the combustion of hydrocarbons and indicates a path that will continue to largely rely on petrol and diesel in the transport sector in the future. Elec, on the other hand, envisages a rapid and comprehensive expansion of electrified applications in transport.

The mobility and traffic scenarios are combined, resulting in a total of four traffic scenarios. The transport developments are flanked by energy demand developments in other sectors taken from the literature as well as framework conditions for the energy sectors. The most important framework condition for the energy sector is the undercutting of the European emissions budget for achieving the 2 °C target. The global framework, in turn, spans two scenarios that either reach the 2 °C target budget or converge to approximately 2.7 °C.

4 Model Implementation

This chapter presents the modelling approach used to assess the transport sector scenarios. Chapter 4.1 deals with modelling the transport sector and explains how energy consumption, costs, and emissions are derived in energy system modelling. The applied method is called SDA. Subsequently, Chapter 4.2 lays out the model extension to incorporate a life cycle perspective. The steps of classic LCA are carried out and it is discussed where the present system assessment deviates from a conventional approach. This approach is referred to as SDLCA. In Chapter 4.3, the key takeaways are summarised in order to be able to classify the further assessment.

4.1 Dynamic Transport Sector Modelling

TraM was initially developed in the course of the Dynamis project [9] and first described by Pichlmaier et al. [101] in 2018. It provides a techno-economic description of the transport sector. Starting from a transport demand, the necessary fleets, and their costs and time-resolved energy consumption are determined. Finally, emissions in the transport sector can be calculated, based on existing emission factors (EMFs). The corresponding workflow is shown in Figure 4.1.

In the following, the fleet calculation is discussed first, as it forms the core of the model. Then, the data basis used to develop the time-resolved energy consumption is explained. Finally, the link to the energy system modelling environment ISAaR is presented, which makes it possible to derive energy-related energy-related GHG emissions.

4.1.1 Fleet Composition

The aim of this part of the model is to determine the number of vehicles of a given vehicle type in a year. A vehicle type is defined by a transport type (e.g. compact car) and a drive system (e.g. diesel combustion engine). The transport demand per transport type is the main input variable in TraM. Furthermore, utilisation factors and annual mileages serve as input data and are initially based on historical data. Both parameters apply equally to all vehicle types within a transport type and across all model years. They are listed for each transport type in Table A.16 in the Appendix.

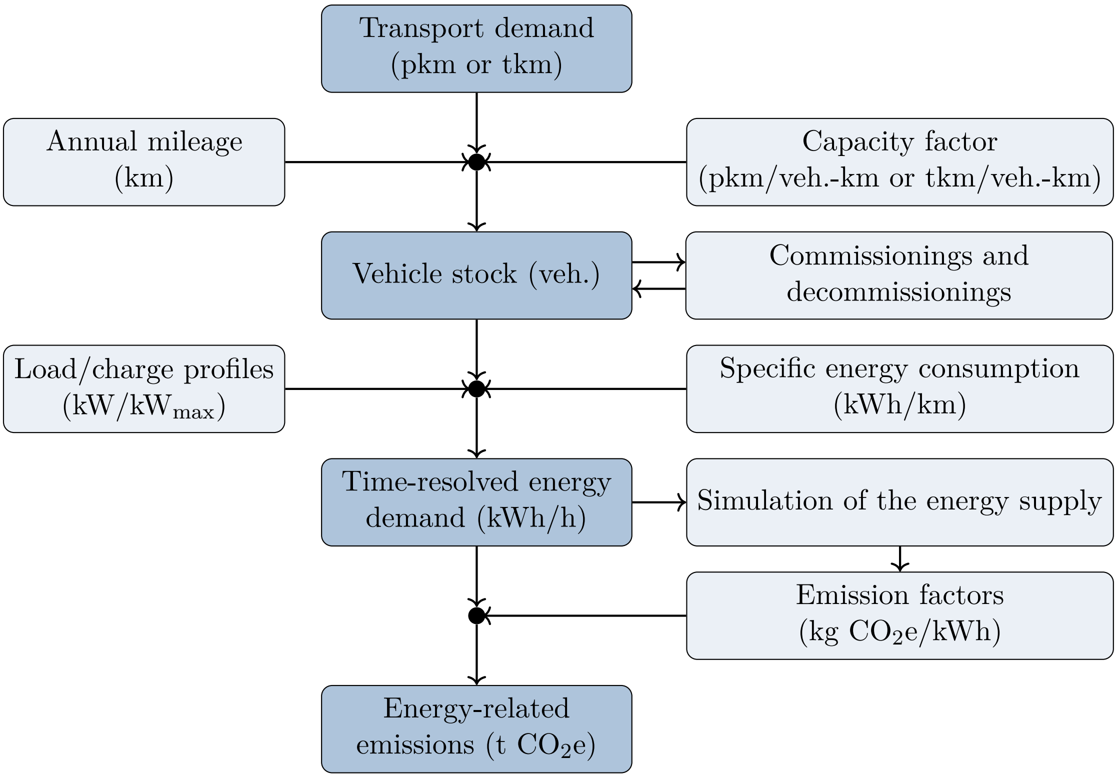


Figure 4.1: Basic structure of TraM

In total, 36 transport types and 157 vehicle types were modelled. Of the 157 vehicle types, 24 are diesel-powered and 29 are petrol-powered. A further 33 vehicle types represent fully electrified vehicles whereby 12 are equipped with plug-in hybrid systems that combine electric and petrol engines, and 26 are hydrogen fuel cell electric vehicles. The remaining vehicle types are either CNG-ICEV, LPG-ICEV, or HEV. Aircraft are assumed to be equipped with turbines using jet fuel. A complete list of which vehicle types are used in which transport types can be found in the Appendix, in Table A.17.

A stock and flow model describes the development for each transport type until 2050. In the following, the principle behind the stock and flow model is explained. The changes in fleet composition due to commissionings and decommissionings are thereby represented in a matrix form.

The Principle of a Stock and Flow Model In the context of this work, a stock and flow model is understood as the representation of a transport type and its stock. The stock of a transport type encompasses all units within the respective vehicle types whereby the number of units within a transport type n_{tt} in a certain year t is defined by the corresponding transport demand of the type D_{tt}:

$$n_{tt,t} = \frac{D_{tt,t}}{\kappa_{tt} \cdot m_{tt}} \tag{4.1}$$

Here, κ_{tt} corresponds to the capacity factor and m_{tt} to the annual mileage of the transport type tt. The transport demand D_{tt} is set by exogenous framework assumptions. The stock in year t consists of the stock in year $t-1$ plus commissionings c_{tt} and minus decommissionings d_{tt} in year t:

$$n_{tt,t} = n_{tt,t-1} + c_{tt,t} - d_{tt,t} = n_{tt,t-1} + \sum_{i} c_{vt,t} + d_{tt,t} \tag{4.2}$$

Analogous to the stock of a transport type tt, its commissionings c_i correspond to the sum of commissionings for all respective vehicle types c_{tt}. In the concept of stock and flow, c_{tt} and d_{tt} represent the flow.

Commissionings and Decommissionings The commissionings represent the only scenario variable to determine the future mix of vehicle types within a transport type. The number of commissionings of a transport type equals the required number of vehicles minus the existing vehicle stock plus the number of decommissionings for a given year. However, their vehicle types remain to be determined. Commissionings are a realistic parameter that can be intuitively understood in the context of the historical development and the status quo of the transport sector (also see Chapter 3.1.2). In addition, focusing on commissionings prevents overestimating the transformation speed in the sector. The annual number of decommissionings is modelled as the sum of all vehicles reaching their end-of-life age. For street vehicles, this is endogenously defined by a probability distribution for each transport type. In the case of the private car transport type, the probability distribution is derived from the historical distribution over the last 20 years [102]. For LDVs, MDVs, HDVs, semi-trailers, buses, and motorbikes an average lifetime was determined [103]. Based on the average service life and the age structure in the stock [102], a standard deviation was determined for the transport types and thus a probability distribution for the decommissioning could be derived. The resulting probability distributions are shown in Figure 4.2.

For all other transport types, a fixed average lifetime was determined. Based on this, an end-of-life age is assigned to each vehicle as soon as it enters the transport system. The only exception is car sharing vehicles which have a service life of 4 years, after which they are transferred to the fleet of private vehicles. The production expenditure and the associated costs and emissions are accounted for on the basis of the first use. A compilation of the average lifetimes of all vehicle types is listed in Table A.16 in the Appendix.

Representation in Matrix Form Knowing the time of commissioning and decommissioning allows for the determination of an $N \times N$ matrix $\mathbf{A_{vt}}$ for each vehicle type. Each element $a_{vt,i,j}$ of the matrix contains the year of commissioning i and the year of decommissioning j and each matrix represents one scenario. The results are obtained for the years between 2020

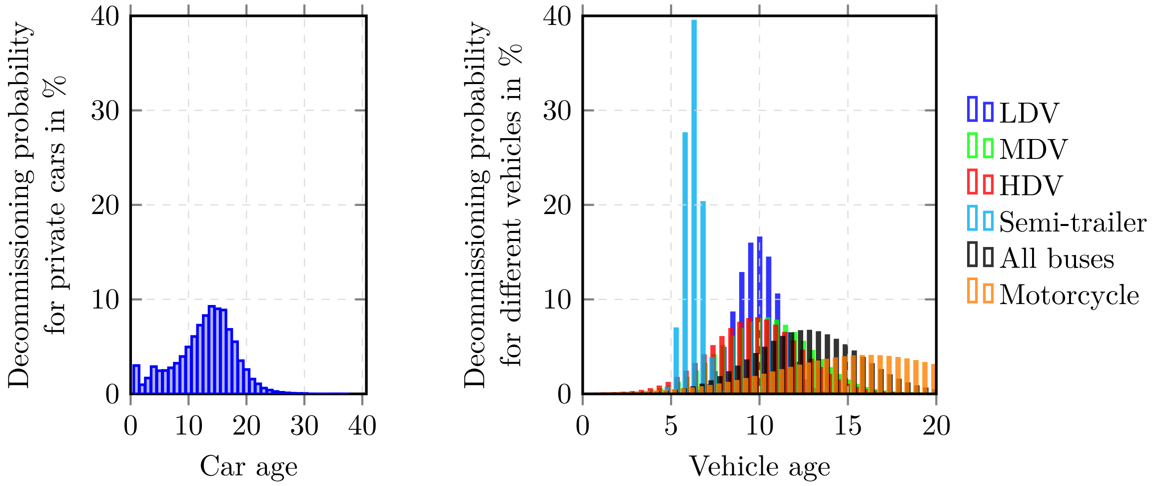


Figure 4.2: Decommissioning probability for privately used cars (left) and other street vehicles (right) depending on the vehicle age in years

and 2050. To accurately depict the status of 2020, the matrix contains elements from the year 2010 onwards. Thus, $N = 41$ and $\mathbf{A_{vt}}$ is a 41×41 matrix.

$$\mathbf{A_{vt}} = \begin{pmatrix} a_{vt,2010,2010} = 0 & a_{vt,2010,2011} & \cdots & a_{vt,2010,2050} \\ 0 & a_{vt,2011,2011} = 0 & \cdots & a_{vt,2011,2050} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & a_{vt,2050,2050} = 0 \end{pmatrix} \tag{4.3}$$

Since vehicles are decommissioned no sooner than 1 year after commissioning, all elements on the diagonal of the matrix and below are zero:

$$a_{vt,i,j} = 0 \qquad \forall i \geq j \tag{4.4}$$

The matrix notation allows the following definitions:

- The total number of commissionings in year t is represented by the sum of the row t and is thus defined as: $\sum_{j=1}^{N} n_{t,j}$
- The total number of decommissionings in year t is represented by the sum of the column t and is thus defined as: $\sum_{i=1}^{N} n_{t,j}$
- The total number of vehicles in the stock in year t is represented by the sum of all elements with a row number $\leq t$ and a column number $\geq t$ and is thus defined as: $\sum_{i=1}^{t} \sum_{j=t}^{N} n_{i,j}$
- The total number of vehicles in the stock in year t, commissioned in x, is represented by the sum of all elements in row x with a column number $\geq t$ and is thus defined as: $\sum_{j=x}^{N} n_{t,j}$

An exemplary application of the matrix was the usage to evaluate how many electric vehicles exit the system in a given scenario to determine the recycling potential for lithium and cobalt by Regett et al. [104]. Furthermore, the annual stocks are needed for the derivation of production emissions in Chapter 4.2.

The representation of shared vehicles is a special case as they have an average lifetime of only 4 years compared to privately used vehicles with 12.8 years. After their years in service as shared vehicles, they switch to the privately used vehicle fleet whereby the time in shared use reduces their lifetime as privately used vehicles.

4.1.2 Energy Consumption

In the next step, time-resolved energy consumption is derived in the model. First, the total energy consumption per vehicle type is derived and then its temporal resolution is determined using specific load and refuelling profiles.

Energy Demand The total energy demand of the transport sector is the sum of the energy demands of all vehicle types. Thereby, the energy demand of a certain vehicle type in year t is described as

$$E_{vt}(t) = n_{vt}(t) \cdot e_{vt}(t) \cdot m_{tt}, \tag{4.5}$$

where m_{tt} is the annual mileage of the transport type, n_{vt} is the total number of vehicles of the vehicle type, and e_{vt} is the specific energy consumption of the vehicle type. The specific energy consumption is one of the most important input parameters for further consideration. Due to its high relevance, it is discussed in more detail below for individual vehicle types. Figure 4.3 shows the specific energy consumption for all vehicle types in cars.

It should be noted that the values reflect the specific energy consumption of new registrations in the respective years. For vehicles in the stock, higher values would result in the respective years, which can be derived using the matrix described in Equation 4.3.

For 2020, the values were derived for current vehicles by using real consumption values rather than according to the Worldwide Harmonised Light Vehicles Test Procedure (WLTP). Hereby, the data was derived from Bründlinger et al. [105] and subdivided for the different vehicle size classes with the help of Schande [106]. From Figure 4.3, it is apparent that the specific energy consumption of electrified vehicles (BEVs, HEVs, PHEVs, FCEVs) is lower compared to ICEVs. Moreover, the specific energy consumption of BEVs and FCEVs decreases more than that of other propulsion systems. For PHEVs, the energy consumption does not decrease any further after reaching the maximum electric driving share in 2040. This applies to all transport types. In order to get a picture of the transport types, Table 4.1 presents an

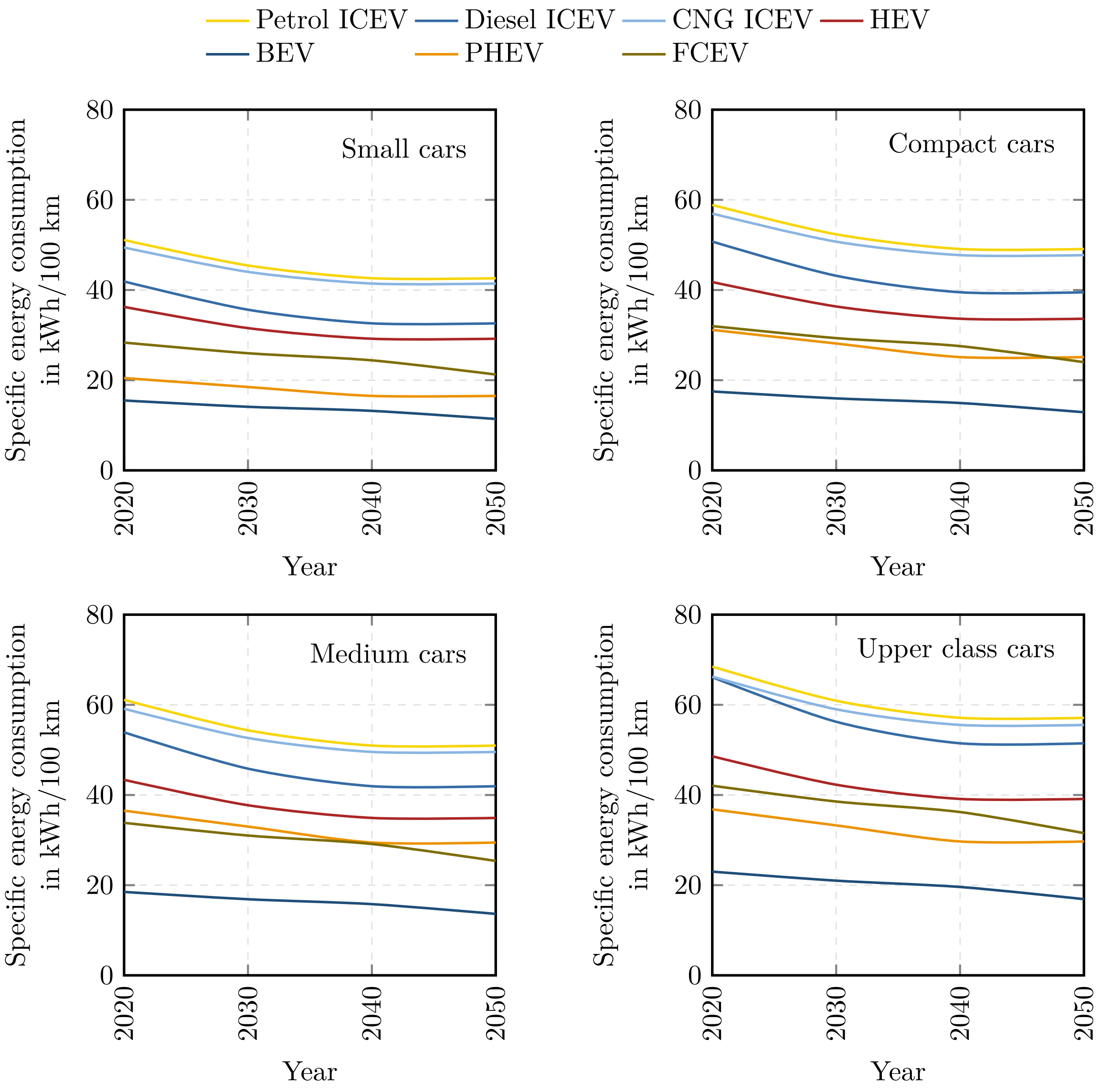


Figure 4.3: Specific energy consumption for the vehicle types in cars; graphs show the data for small cars (top left), compact cars (top right), medium cars (bottom left) and upper class cars (bottom right); also see Table A.12 in the Appendix

overview of exemplary vehicles according to the statistics of the Federal KBA [65]. The share of the total stock in 2020 is listed in the column on the right.

The upper class vehicle type comprises several segments and contains the largest share of vehicles. Their similar characteristics concerning specific energy consumption and annual mileage justify this grouping.

The specific energy consumptions of all vehicle types are listed in the Appendix in Tables A.12, A.13, A.14, and A.15. The data was compiled from various studies and statistics whereby particular attention was paid to consistency within a given transport type. As was the case for passenger cars, data from Bründlinger et al. [105] is used for LDVs and MDVs. Commercial

Table 4.1: Exemplary vehicles for the four vehicle segments in private cars and their share of the total vehicle stock as derived from [107]

Vehicle segments	Exemplary vehicles (KBA segments)	Share of total car stock
Small car	VW Up (A), Ford Fiesta (B)	26.0 %
Compact car	VW Golf (C)	25.3 %
Medium car	Audi A4 (D)	13.0 %
Upper class car	Audi A6 (E), Tesla Model S (F), BMW X2 (G), Audi Q7 (H), Mercedes CLK (I), Kia Soul (J), VW Touran (K), VW Transporter (L)	35.6 %

vehicles with a gross mass above 12 t are divided into HDVs and semi-trailers and data from KBA is used for the specific energy consumption of HDVs [64]. For the energy consumption of semi-trailer trucks, Kühnel et al. [108] provided a more specific source by examining the technologies for this segment in great detail.

For the specific energy consumption of trains, expert interviews were conducted with a large German train operator and the values were adjusted according to the total energy consumption using the values of the German Federal Ministry for Digital and Transport [59]. The energy consumption of inland vessels and aircraft is derived from the corresponding transport statistics [62, 109] of the Federal Statistical Office of Germany and data from Schlesinger et al. [73] in the form of a top-down approach. A top-down approach was also adopted for buses. Here, the total energy consumption from the data of the German Federal Ministry for Digital and Transport [59] is allocated to coaches and regular buses and their size classes based on the KBA [73] and Schlesinger et al. [110]. The number of vehicles is then used to determine the time-resolved energy demand.

Time-Resolved Energy Demand Time-resolved energy demands are required as input data in energy system modelling to evaluate repercussions on the supply sector. The required temporal resolution decreases with the storability of the energy carrier. For electricity, an hourly resolution is chosen, while a daily resolution is used for gases. For liquid energy carriers such as petrol or diesel, the initial annual resolution is applied. The derivation of load profiles for individual vehicle types is explained below and the basis for this has already been described in Conrad et al. [9]. In the following explanations, a summary is given for all load profile methods.

First, the procedure is explained for electric vehicles. The methodology of modelling charging profiles for electric, private and commercial cars and LDVs was explained in detail by Fattler et al. [111, 112]. In addition, the chosen procedure explained below and the underlying assumptions were already described in [9]. Private and commercial transport in Germany differ in terms of composition and mobility behaviour. Accordingly, two different mobility studies are used to derive suitable charging profiles. The mobility behaviour in private transport is described in the study 'Mobility in Germany 2017 (MiD2017)' [40] while commercial traffic, on the other hand, is discussed in the study 'Motor Vehicle Traffic in Germany 2010 (KiD2010)' [113]. Both studies provide a broad base of empirical data for the respective areas. The mobility behaviour shown in the studies is then filtered and made plausible with regard to the future users of electric vehicles. Daily driving profiles are derived on the basis of the remaining data for mobility behaviour while annual driving profiles are determined from the daily driving profiles, thereby also taking holiday periods, public holidays, and bridging days into account. Finally, charge profiles are calculated based on temperature time series, assumptions about future battery and charging capacities, and charging behaviour. Besides direct charging, emission-optimised charging and Vehicle-to-Grid (V2G) are considered. The assumptions for the charging power at different locations and the battery capacities for BEVs and PHEVs can be found in Tables A.18 and A.19 in the Appendix. Figure 4.4 schematically illustrates the procedure used to derive the charging profiles.

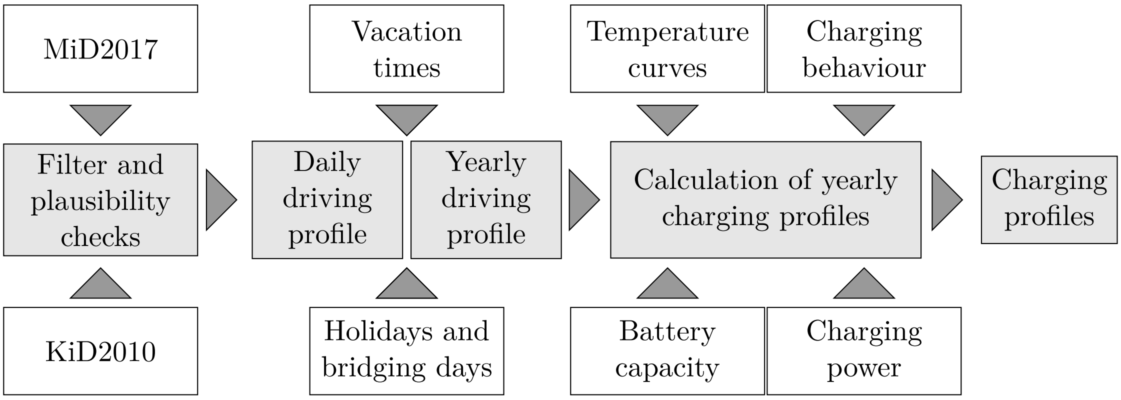


Figure 4.4: Schematic sequence of the derivation of charging profiles; own illustration after Conrad et al. [9]

The methodology does not cover multi-day trips or charging at fast charging stations. Accordingly, the annual mileages derived here are lower than those in Table A.16. This delta in energy consumption is attributed to public fast charging stations and data from a study by Nexant Inc. [114] is used to model public charging patterns whereby hourly charge profiles were derived from the fuel demand at 387 conventional filling stations in the US. Even though it can be assumed that the refuelling behaviour differs from that of German electric car drivers, charging at fast charging stations is similar to refuelling at petrol stations. Although fast charging currently takes longer than conventional refuelling, the time penalty is assumed to be negligible since the duration of the charging process is still within the selected time resolution of 1 hour. Furthermore, the day and night distribution is due to mobility behaviour, which can be classified as similar in both cases and thus the simplification is accepted at this point. The sum of normal and fast charging energy demand results in a total charge profile for electric vehicles. For illustration purposes, Figure 4.5 shows a sample week of BEV charge profiles in the medium passenger car segment. Due to poor data availability, it was assumed that shared vehicles have the same load profile as privately used vehicles.

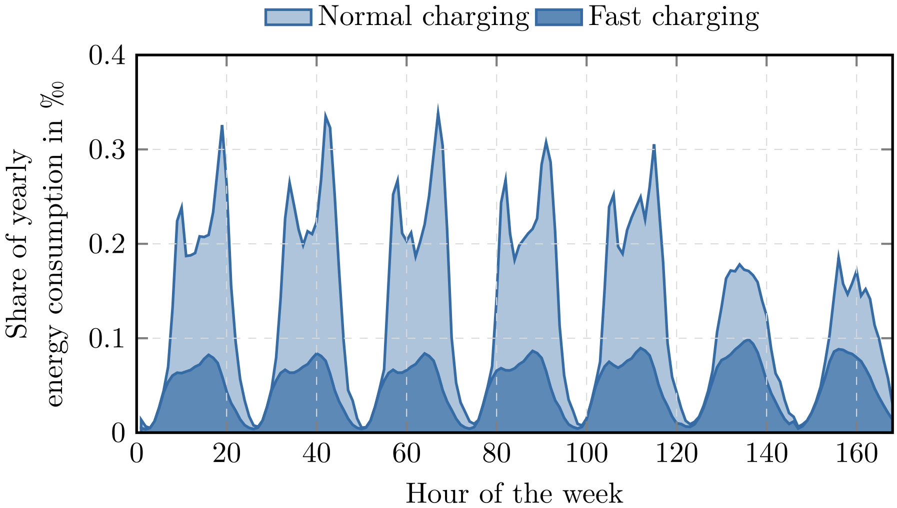


Figure 4.5: Weekly charge profile of BEVs of the medium car segment in a sample week containing a normal and a fast charging share

In the following, the charge profile of electric trucks and buses is discussed. The data is based on hourly traffic counts on motorways and national roads by the Federal Highway Research Institute [115]. The data distinguishes between buses, semi-trucks, and other large trucks. Only the number of vehicles is counted and there is no information on route lengths or the duration of the trips. First, the counted vehicles are standardised over the entire year. This means that it is assumed that every vehicle counted in an hour has already been driving for an hour. In addition, the assumption is made that the spatial distance between counting points is sufficient to avoid double counting vehicles within 1 hour.

While OCSTs are assumed to charge while driving, other electric vehicles are assumed to charge when parked. Here it is assumed that vehicles are used as much as possible to maximise economic efficiency, so they are always charging when parked. However, at this stage it must also be mentioned that these assumptions may lead to an implicit load smoothing and thus the maximum load of the corresponding vehicle types could be underestimated. Figure 4.6 shows an example of the resulting load curve in 1 week for OCST and the weekly load curve over 1 year for all trucks and buses.

To create a load profile for electric rail vehicles (freight, local, long-distance, high-speed, inner city), data from Gerhardt [116] was used which describes the load profile within a typical week. Based on this load profile, day types Monday to Friday, and Saturday and Sunday were derived whereby bridging days correspond to Saturdays and public holidays to Sundays. These representative days were then distributed over the entire year. The load profile for a sample week is shown in Figure 4.7.

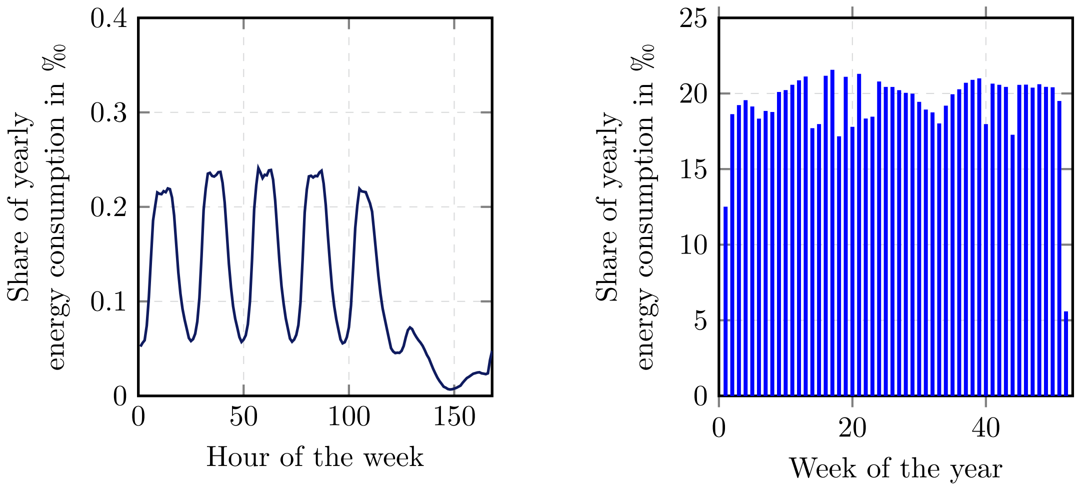


Figure 4.6: Weekly load profile in week number 3 of OCSTs (left) and weekly share of the total energy consumption of trucks and buses, based on data derived from the Federal Highway Research Institute [115]

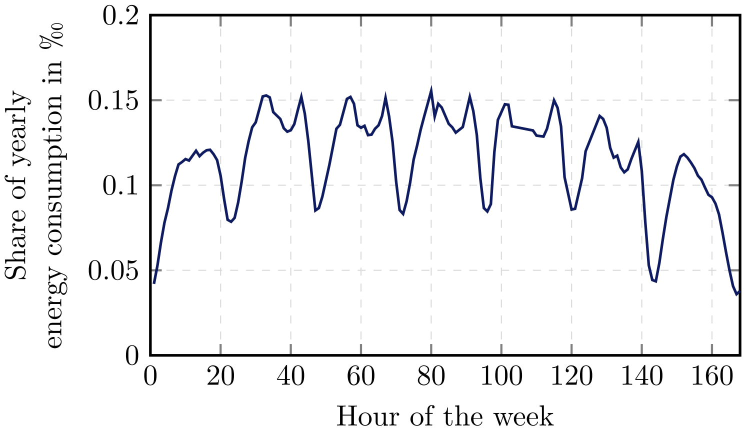


Figure 4.7: Weekly load profile of trains in a sample week based on data derived from [116]

Following the procedure proposed in the dissertation by Mayer [117], the previously mentioned data from Nexant Inc. [114] is used to derive load profiles for gas and hydrogen vehicles in road transport. Since the refuelling behaviour of FCEVs and CNG ICEVs can be classified as similar and only daily profiles are relevant for the present work, aligning their load profiles seems appropriate. As with the electric load profiles for railways, the same three-day types are distinguished in terms of gas demand. However, the differences between the different types of days are insignificant which results in a very homogeneous load profile within 1 year for FCEVs and CNG ICEVs.

For all other vehicle types, the energy demand is assumed as remaining constant throughout the year. As described above, this is an adequate assumption for liquid energy sources due to their good storage properties and therefore the energy demand for hydrogen-powered vessels can also be assumed to remain relatively constant throughout the year.

4.1.3 Energy Supply

In order to be able to calculate emissions in the transport sector without neglecting the possible repercussions on the energy supply sector, the assessment has to include the energy supply sector. For the present study, the model environment 'ISAaR' is used for this purpose. The schematic approach for coupling energy application and energy supply is shown in Figure 4.8.

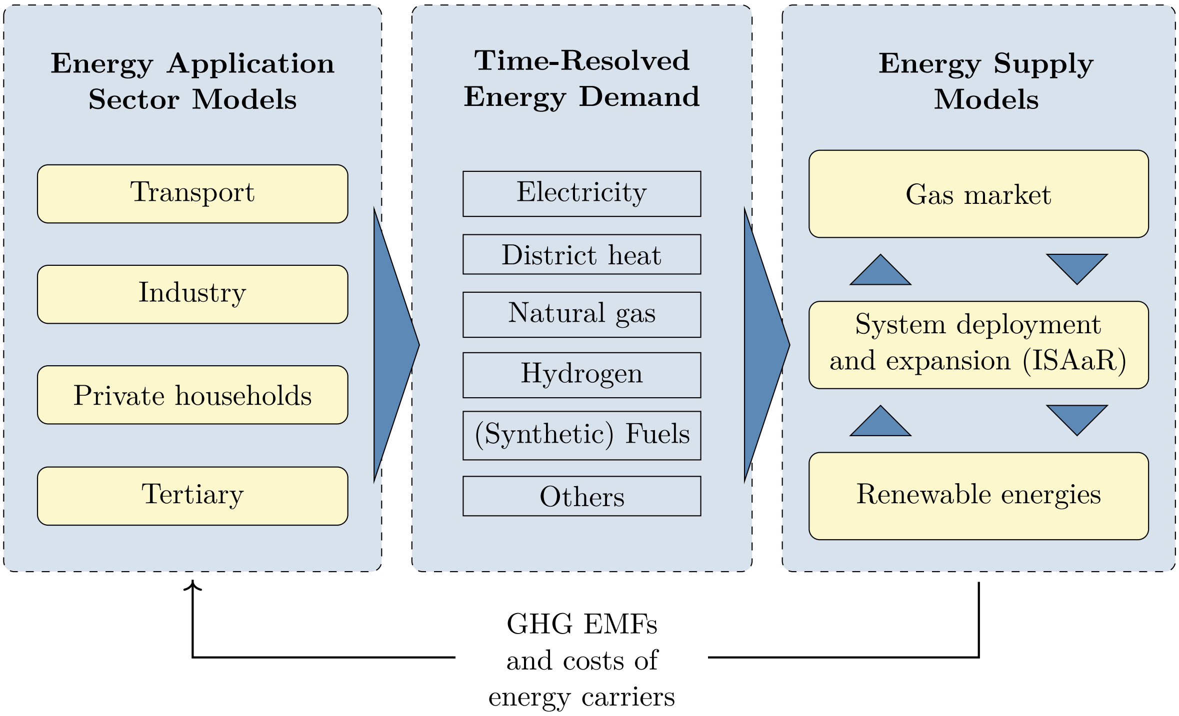


Figure 4.8: Schematic sequence of coupled energy application and energy supply models; own illustration after [9]

According to the illustration, in addition to the loads from the transport sector, the industry, private households, and tertiary sectors must also be considered although their calculation is not part of this dissertation. The necessary values are taken from the scenario *solidEU* (also see Chapter 3.2.2). The energy consumption of all application sectors is then transferred to the energy supply models which subsequently determine a cost-optimal energy supply path to 2050 for each scenario. Finally, the supply models return GHG EMFs and costs for each energy carrier to the sector models. In the following, the models used to derive the energy supply are addressed before the calculation of emission factors is explained in detail.

ISAaR is the core model on the energy supply side [118]. It is a linear optimisation model for system deployment and expansion. As a multi-energy system model, it represents the energy carriers electricity, methane, hydrogen, district heat, and liquid hydrocarbons. The model ensures that the load profiles of the application sectors are covered at a minimal cost. Similarly, the model 'Market and Infrastructure for Gas (MInGa)' [119] calculates a cost-optimal coverage of the gas demand, both from the energy application sectors and from ISAaR. Furthermore, ISAaR includes options for the expansion of renewable energies. Potential locations, installed capacities, and amounts of renewable energy generation are derived on the basis of geographic information systems (GISs) taking into account, for instance, the expected hours of sunshine at a site or the cost of leasing land.

4.1.4 Emission Factors

For further evaluations of the emissions of the transport sector, GHG EMFs are needed for electricity, hydrogen, gas and liquid fuels. The EMFs of the energy carriers depend on each other, as they are coupled via conversion technologies (e.g. gas power plants or electrolysers). Since electricity will play a key role in increasingly defossilised energy systems, the EMFs of the other energy carriers will be calculated starting from the EMF of electricity. To calculate the EMF of electricity, the methodology for consumption-based EMFs from the dissertation of Fattler [120] is used. The consumption-based EMF of electricity considers cross border electricity flows, also reflecting electricity generation and demand in neighbouring countries. The procedure is described in Figure 4.9.

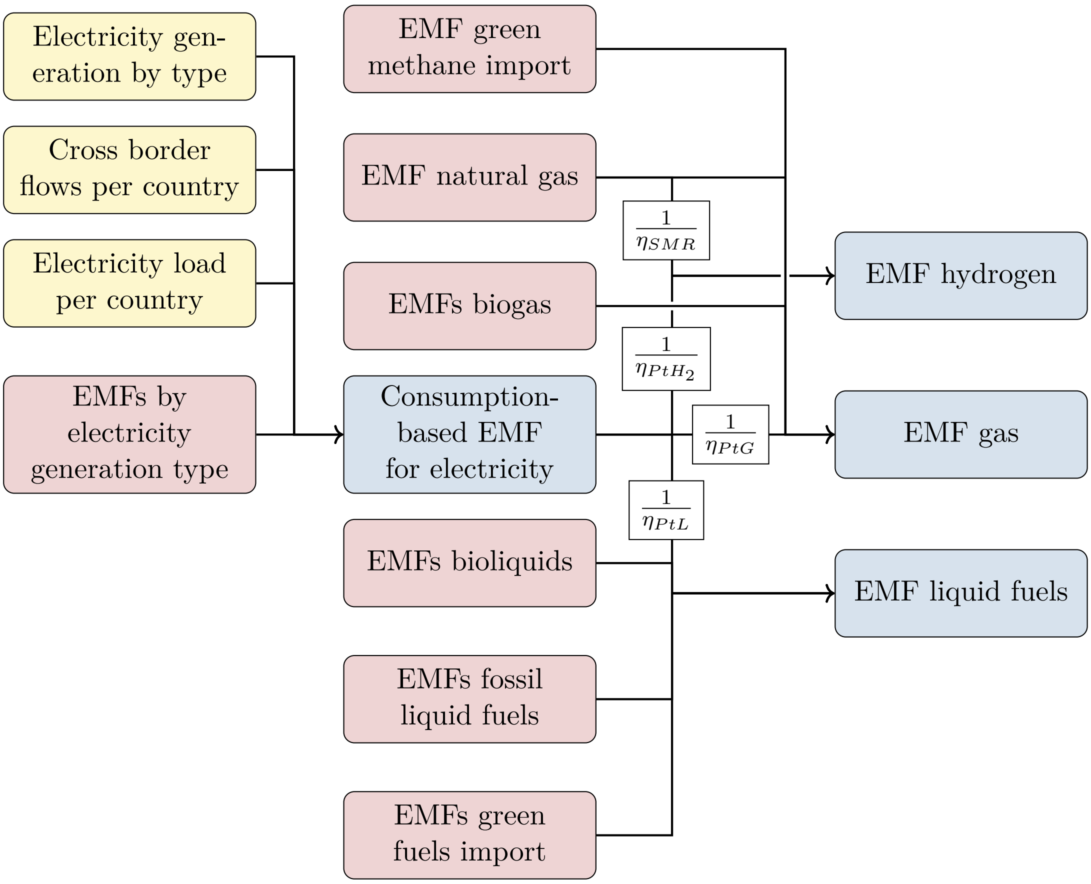


Figure 4.9: Derivation of GHG EMFs for electricity, hydrogen, gas, and liquid fuels

The EMF of electricity is now referred to as emf_{el} whereby emf_{el} is the weighted average EMF of the electricity generation types used:

$$emf_{el} = \sum_{i} \mu_i \cdot emf_i \tag{4.6}$$

where:

emf_i	EMF of the electricity generation type i
μ_i	The share of the electricity generation type i and

Table 4.2 shows the EMFs used for the electricity generation technologies. The EMFs of electricity-only generation technologies are derived from Sacchi et al. [49]. They contain the efficiencies of thermal power plants according to the scenario SSP2-4.5 (also see Chapter 3.2.2) and therefore represent current trends. The technologies implemented include conventional gas turbines, combined cycle gas turbines (CCGTs), oil-fired power plants, and hard coal and lignite-fired power plants. In addition, combined heat and power generation (CHP) technologies are listed. According to the underlying data in the ecoinvent database, the allocation of emissions to electricity and heat is based on the Finnish method. According to Fattler [120], this results in higher emission factors for electricity than with the method of the International Energy Agency (IEA). However, they are lower compared to the Carnot or Efficiency method. As only direct GHG emissions are used in the first approach of this dissertation, emissions arising from the upstream chain are not included. This results in an EMF of zero for all renewable energy technologies.

Table 4.2: Direct GHG EMFs of electricity generation types based on ecoinvent [47] and the dissertation of Fattler [120]

	EMF in g CO_2e/kWh_{el}			
Generation type	**2020**	**2030**	**2040**	**2050**
Gas turbine	550	522	509	497
CCGT	326	316	312	307
Oil	832	863	897	933
Coal	786	763	746	730
Lignite	988	959	937	917
Gas/CCGT CHP	412	412	412	412
Coal CHP	793	793	793	793
Lignite CHP	968	968	968	968
Nuclear	0	0	0	0
All renewables	0	0	0	0

In the model, hydrogen is either produced by electrolysis on the basis of electricity or by steam reforming from natural gas. Accordingly, the emission factor emf_{H_2} of hydrogen can be described as

$$emf_{H_2} = emf_{el} \cdot \frac{1}{\eta_{PtH_2}} \mu_{PtH_2} + emf_{NG} \cdot \frac{1}{\eta_{SMR}} \cdot \mu_{SMR} \tag{4.7}$$

where:

η_{PtH_2}	Efficiency of electrolysis process
η_{SMR}	Efficiency of steam reforming process
μ_{PtH_2}	Share of electrolysis process in hydrogen supply
μ_{SMR}	Share of steam reforming process in hydrogen supply
emf_{NG}	EMF of natural gas

Gas is understood to be a gas mixture that, like natural gas today, largely consists of methane. In the model, gas can not only be produced by fossil natural gas but also by a biogenic process in the fermenter and by the Power-to-Gas (PtG) process. The PtG process is understood to be the electricity-based production of hydrogen with subsequent methanation. Analogous to the production of hydrogen, the EMF of gas is described as follows

$$emf_{Gas} = emf_{NG} \cdot \mu_{NG} + emf_{Bio,G} \cdot \mu_{Bio,G} + emf_{el} \cdot \frac{1}{\eta_{PtG}} \mu_{PtG} + emf_{Imp,G} \cdot \mu_{Imp,G} \tag{4.8}$$

where:

η_{PtG}	Efficiency of PtG process
μ_{PtG}	Share of PtG process in gas supply
μ_{NG}	Share of natural gas in gas supply
$\mu_{Bio,G}$	Share of biogas in gas supply
$\mu_{Imp,G}$	Share of green methane import in gas supply
emf_{NG}	EMF of natural gas
$emf_{Bio,G} = 0$	EMF of biogas, zero by definition
$emf_{Imp,G} = 0$	EMF of imported green methane, zero by definition

In the model, liquid fuels include petrol, diesel, and jet fuel. Although their EMFs are very similar, the fuel supply is modelled separately for each of the three fuels. For alternative supply technologies such as biogenic production via fermenters and the PtL process, the parameters from gas production are applied equally to liquid fuels. In this case, the PtL process is understood as the production of hydrogen via electrolysis and further processing into carbon-based liquid energy carriers by means of the Fischer-Tropsch (FT) processes. This results in the EMF of liquid fuels as described by the following equation:

$$emf_{LF} = emf_{FLF} \cdot \mu_{FLF} + emf_{Bio,L} \cdot \mu_{Bio,L} + emf_{el} \cdot \frac{1}{\eta_{PtL}} \mu_{PtL} + emf_{Imp,L} \cdot \mu_{Imp,L} \tag{4.9}$$

where:

η_{PtL}	Efficiency of PtL process
μ_{PtL}	Share of PtL process in liquid fuels supply
μ_{FLF}	Share of fossil liquid fuels in liquid fuels supply
$\mu_{Bio,L}$	Share of biogenic liquid fuels in liquid fuels supply
$\mu_{Imp,L}$	Share of imported green fuels in liquid fuels supply
emf_{FLF}	EMF of fossil liquid fuels
$emf_{Bio,L} = 0$	EMF of biogenic liquid fuels, zero by definition
$emf_{Imp,L} = 0$	EMF of imported green fuels, zero by definition

Besides the relationship of electricity for the production of other energy carriers, the described approach neglects further possible feedback between EMFs. For example, the storage of hydrogen for seasonal balancing in electricity generation is not considered in the EMF of electricity even though it is used in the energy supply. A corresponding system of equations has already been formulated for Germany in ISAaR [118], but has not yet been transferred to European modelling. Since energy supply is not the focus of this thesis, this simplification is accepted.

4.1.5 Emissions of the Transport Sector

The previously derived energy consumption and emission factors now allow the calculation of total emissions in the transport sector. For the emissions per vehicle type Em_{vt}, the formula is as follows:

$$Em_{vt} = E_{vt} \cdot emf_{vt} \tag{4.10}$$

According to Table A.17 in the Appendix, one energy carrier and its corresponding EMF is assigned to each vehicle type. The sum of all emissions of the vehicle types within a transport type results in the emissions Em_{tt} of the transport type. Finally, the sum of all emissions of the transport types in the transport sector results in the total emissions Em_{tot} of the transport sector:

$$Em_{tot} = \sum_{tt} Em_{tt} = \sum_{tt} \sum_{vt} Em_{tt,vt} \tag{4.11}$$

As described above, these emissions include the direct, energy-related GHG emissions of the transport sector and although they do not fully correspond to the system boundaries of national inventory reports, they are similar. The present approach includes international air traffic as well as emissions from the provision of electricity and hydrogen. Moreover, the bottom-up approach in road transport only includes vehicles registered in Germany. In the case of the Climate Protection Act, however, emissions are assessed top-down, based on refuelling data in Germany. This leads to accounting differences when refuelling German vehicles abroad. Likewise, the approach according to the Climate Protection Act neglects the fact that Germany is a transit country in Europe and therefore foreign vehicles also refuel in Germany. The resulting deviations are thus particularly noticeable in road freight transport.

4.1.6 Total Costs of the Transport Sector

In order to give the ecological assessment an economic classification, the costs of the sector are also calculated. For this reason, each vehicle type is associated with capital expenditures (CAPEX) and fixed operational expenditures (OPEX). Analogous to emissions, costs are considered from a system perspective which means that taxes and levies are not included and costs rather than prices are used as far as possible. Because of limited data availability, this was not possible in each case. For the cost evaluation, the capital expenditures (CAPEX) of vehicles is allocated over their lifetimes, according to the annuity method.

The CAPEX values contain a proportion of new, consumer-related infrastructure for road vehicles such as, for example, wallboxes, charging stations, or hydrogen filling stations. Similarly, OCSTs include the pro rata costs of new overhead lines. Diesel or petrol vehicles do not have such additional costs as they can utilise existing infrastructure. Other infrastructure considerations, such as pipelines or power grids, are not part of the evaluation. The fixed OPEX values contain expenditures for maintenance and servicing and are defined as a share of the CAPEX. The costs are derived from Bayer et al. [121] and Conrad et al. [9], and are listed in Tables A.20, A.21, A.22, and A.23 in the Appendix.

The last cost parameter, the variable OPEX, reflects the energy costs. They are provided by the energy system model according to Figure 4.8. In this dissertation, the term 'costs' is used for energy carriers, although some components are prices. Thus, while the modelling via ISAaR results in a market price for energy carriers, the components contain both costs and prices, e.g. in the construction of the units. A more detailed discussion about costs and prices in the energy supply can be found in the dissertation by Guminski from 2022 [122].

4.2 LCA Expansion of the Transport Model

For the second approach, TraM is now extended to include a life cycle perspective whereby energy-related GHG emissions will be expanded by the upstream chain of energy carriers. Furthermore, a valuation methodology must be applied that covers the production and disposal of vehicles. The general concept of the LCA expansion and the related results were first introduced by Pichlmaier et al. in 2021 [123].

The methodology for conducting an LCA study is defined in ISO 14040 and 14044. Thereby, LCA is described as a method for assessing the ecological impact of a product or service over its entire life cycle. In the present case, the system 'German transport sector' is evaluated. According to the ISO standards, four iterative steps have to be completed for the assessment:

1. Definition of goal and scope (Chapter 4.2.1)
2. Life cycle inventory (Chapters 4.2.2, 4.2.3, 4.2.4, and 4.2.5)
3. Life cycle impact assessment (Chapter 4.2.6)
4. Life cycle interpretation (Chapter 5.2)

The first three steps will be performed in the following chapters while the life cycle interpretation is conducted in the context of the assessment.

4.2.1 Definition of Goal and Scope

This LCA study pursues purely scientific objectives for which GHG emissions are to be determined for scenarios of the transport sector, beyond country and sector boundaries. This means that all environmental impacts for the production, operation, and disposal of transport sector elements are also attributed to the sector. Relevant findings with regard to possible emission reduction measures are to be derived using e.g. contribution analyses. Additionally, the LCA will be compared with the tool of energy system analysis from Chapter 4.1. Accordingly, this aspect primarily addresses the scientific community.

Within the scenarios, LCAs are conducted for each model year. The function of the transport system, as defined in Chapter 3.1, is to change the location of people and goods. Consequently, the functional unit in this LCA is the transport performance (in pkm and tkm) to be covered in a given year. The impact category to be assessed is climate change and the main indicator is the global warming potential over 100 years (GWP100). The system boundaries for the evaluation are shown in Figure 4.10.

The considered product system of the transport sector consists of different vehicle types as described above. Their assessment includes the acquisition of materials, the production and operation of vehicles, and their end-of-life. The so-called direct emissions may occur in the vehicle operation phase. For example, the operation of a diesel car produces GHG at the tailpipe while indirect emissions arise in the upstream chain of the individual stages, for example, in the mining of raw materials for the production of electric vehicles. Due to its particular importance, special attention is paid to the energy consumption across all life cycle stages and thus all processes are evaluated in a dynamic energy system setting, in accordance with the chosen scenarios of German and global energy supply. The term dynamic refers to the direct interrelation of the provision of the energy carriers with the consumption and with each other. Finally, emissions are summed up over all vehicles for each year to derive the total annual emissions.

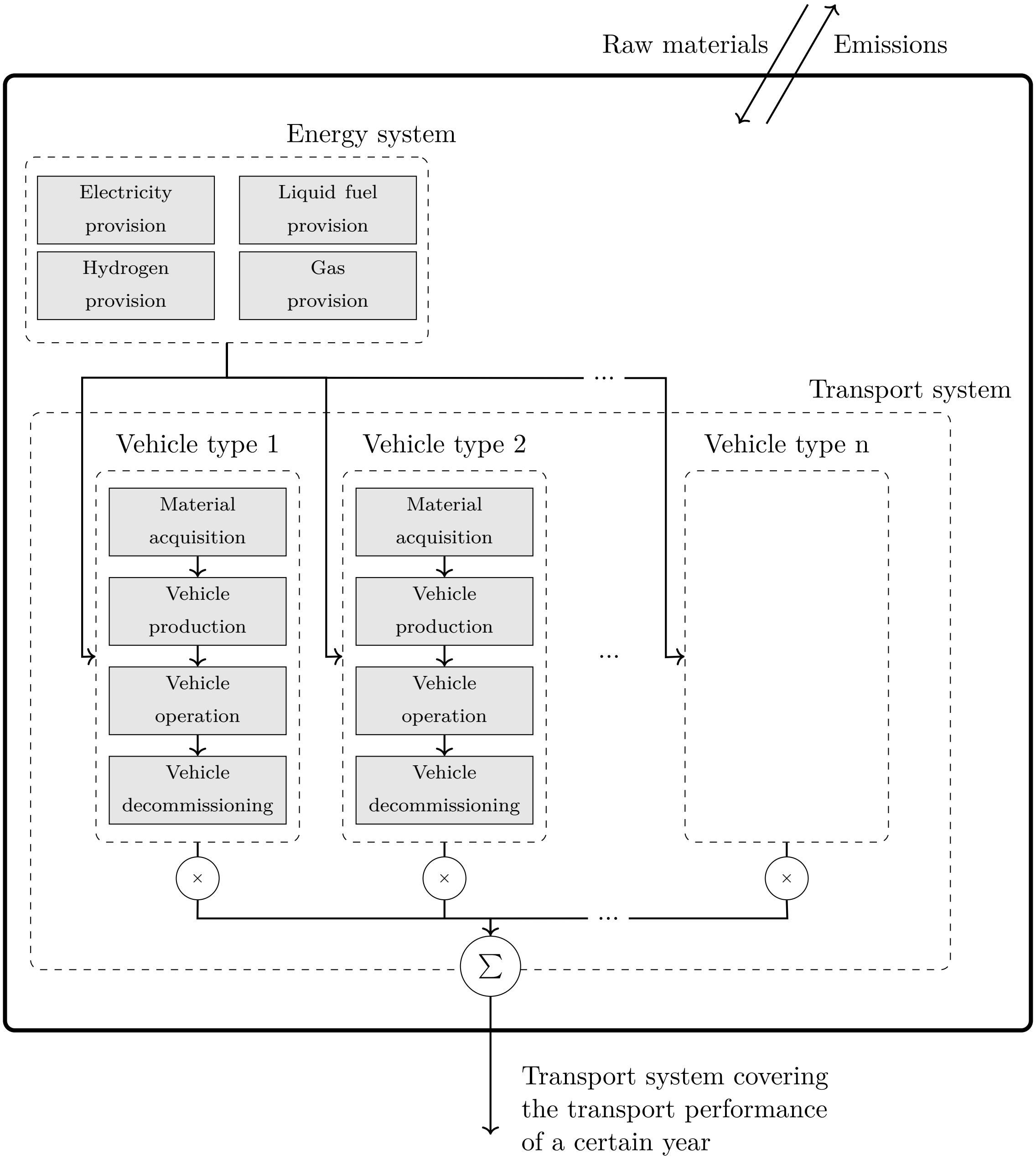


Figure 4.10: System boundaries of the LCA

The broad product system results in several limitations compared to conventional LCA studies. For example, a large part of the data is retrieved automatically from databases that cannot be validated in detail due to the amount of data. As is usual with prospective LCAs, several assumptions must be made, some of which are also taken from the underlying databases. In the present case, regular plausibility checks are carried out and more detailed investigations are made for vehicle types with large shares in the environmental impact. However, in general, the quality of the data is found to be high. All the data that is used is publicly available, although some are only accessible through commercial databases.

4.2.2 Integrating Life Cycle Inventories

The next step of the LCA is the inventory analysis. This phase includes data collection, preparation, and validation for all corresponding processes. Finally, the inputs and outputs are to be referred to the functional unit. This results in a general LCI of the whole transport sector containing all material flows and emissions within the defined system boundaries.

In the present case, the data to be generated are closely related to the results of the fleet modelling. Individual LCIs are developed for the scenario years to account for the developments over time. The general scheme of the derivation of LCIs, and hence the model expansion, can be seen in Figure 4.11.

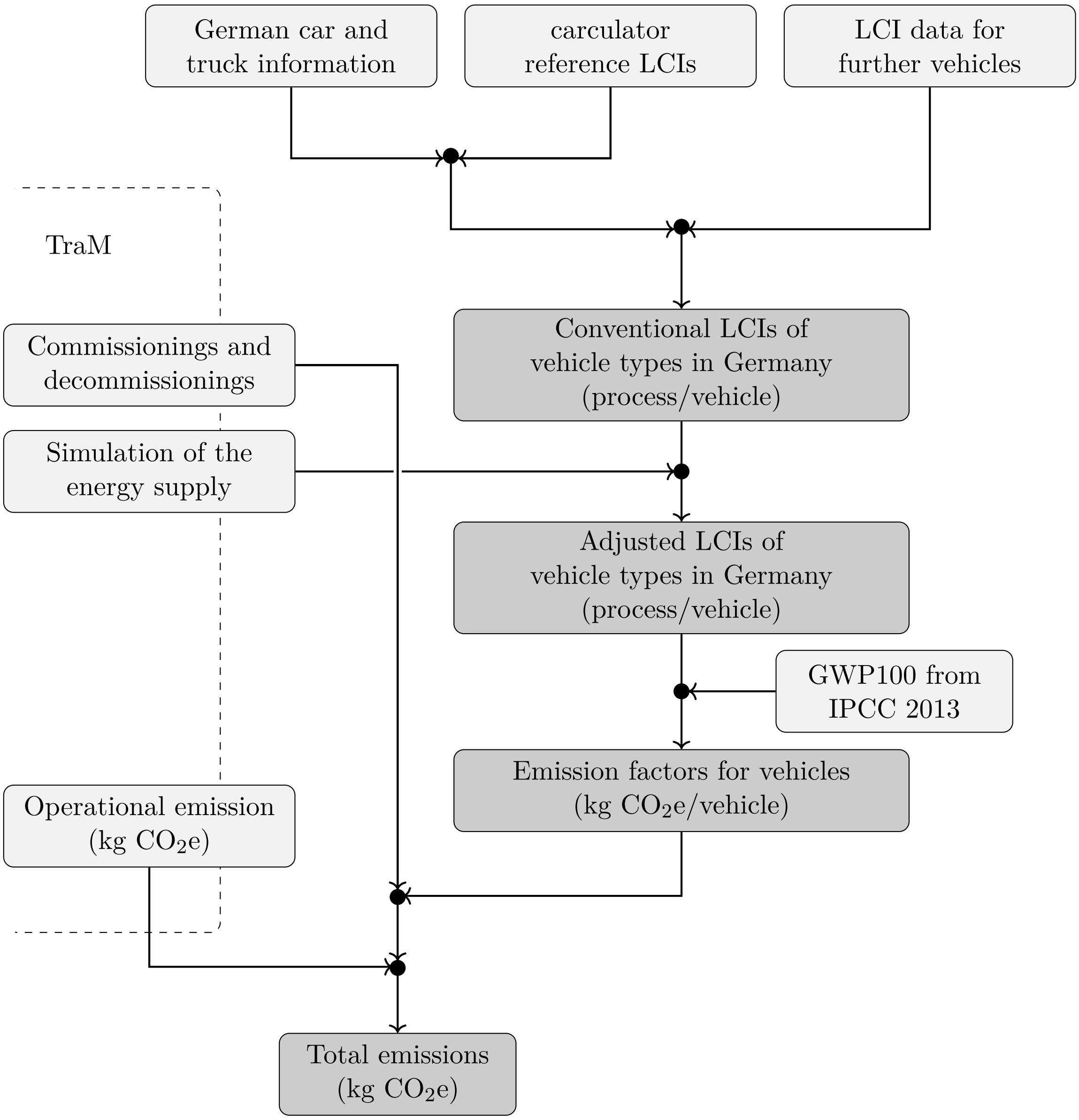


Figure 4.11: Basic structure of the LCA extension of TraM

In a first step to creating the inventories, the carculator [124] and carculator truck [125] databases are fed with information on German road vehicles. The carculator contains LCIs of current and future road vehicles. The information on the German transport sector contains the assumptions made for the vehicle types according to Tables A.16 and A.19 in the Appendix. LCI data for the other modes of transport were compiled from various sources which results in a complete LCI data set for the German transport sector. In a subsequent step, the background data is adjusted, so that the assumptions for global energy supply are consistent with the scenarios of the German and European energy supply sectors. Thereby, the term 'background data' includes all processes that are not in the directly modelled foreground. These are taken from other sources accordingly. The resulting adjusted LCI data set can now be used to derive emission factors. The environmental indicator GWP100 of the IPCC report from 2013 is chosen to map the impact category of climate change [126] (also see Chapter 4.2.6). From this, EMFs are now derived for all vehicles types. These are to be multiplied by the number of commissionings and decommissionings in the respective years derived from TraM (also see Figure 4.10). The result is the emissions in the production and disposal of all vehicles in the transport sector in 1 year. Together with the energy-related GHG emissions, the total emissions of the transport sector can thus be derived.

In the following, the individual steps are described in more detail. In Section 4.2.3, the expansion of the operational emissions will be discussed. Subsequently, the derivation of the conventional LCI data sets is described in Section 4.2.4, followed by its adjustment process in Section 4.2.5. Finally, the calculation of total emissions is explained in Section 4.2.6.

4.2.3 Expansion of Energy-Related Emission Factors

The derivation of the operational EMFs follows the procedure already described in Figure 4.9. The corresponding calculations are now supplemented by data about the construction and dismantling of the energy conversion plants. Finally, the background data is also adjusted according to the global energy scenarios described in Chapter 3.2.2.

Electricity The system response from ISAaR for the composition of electricity supply in the SDA is used analogously for the SDLCA. However, in order to derive EMFs for the LCA, the categories of electricity generation in ISAaR have to be matched with those provided by the ecoinvent database. The categorisation is shown in Table 4.3.

In addition, lower resolutions exist for some power generation units of ecoinvent in ISAaR and these must be allocated accordingly. Table 4.4 lists the disaggregations for the corresponding technologies whereby the allocations used correspond to those of the status quo and any changes in future scenarios are not taken into account. For nuclear power plants, the simplification is acceptable due to the phase-out in 2022. In the area of solar and wind energy, no further breakdown is possible due to a lack of more in-depth data. For wind energy in partic-

Table 4.3: Matching of generation types between ISAaR and ecoinvent

ISAaR generation type	ecoinvent generation type
Nuclear	Electricity production, nuclear
Lignite CHP	Heat and power co-generation, lignite
Lignite	Electricity production, lignite
Gas turbine	Electricity production, natural gas
Gas steam and power CHP	Heat and power co-generation, natural gas, combined cycle power plant
Gas steam and power	Electricity production, natural gas, combined cycle power plant
Oil	Electricity production, oil
Hard coal CHP	Heat and power co-generation, hard coal
Hard coal	Electricity production, hard coal
Biomass CHP	Heat and power co-generation, wood chips
Biogas CHP	Heat and power co-generation, biogas
Hydro, run-of-river	Electricity production, hydro, run-of-river
Solar (roof)	Electricity production, photovoltaic, slanted-roof installation
Solar (open site)	Electricity production, photovoltaic, open ground installation
Wind onshore	Electricity production, wind, onshore
Wind offshore	Electricity production, wind, offshore
Geothermal	Electricity production, deep geothermal

ular, however, it can be assumed that the number of turbines <1 MW will continue to decline. The GWP100 (IPCC 2013) of small and medium-sized turbines are similar 16.2 g CO_2e/kWh and 17.0 g CO_2e/kWh [47]. The impact of large wind turbines, however, is much higher at 30.3 g CO_2e/kWh due to a much higher material input, especially with regard to concrete, steel, copper, and aluminium. This overcompensates for the higher production of electricity. It is worth mentioning that, in this case, a consequential LCA (also see Chapter 4.2.4) would lead to a more positive valuation of large turbines, as the production of a larger amount of electricity is weighted more heavily.

Additionally, processes were introduced for the application of GHG-neutral gases and liquids. These hypothetical processes build on the conventional variants and save as much CO_2 in the supply as would be released in a perfect combustion. This ensures that the construction and decommissioning of the plant is still included in the results, while the combustion of the energy carrier is accounted for with zero. Additional processes are included to reflect the construction and maintenance of the necessary infrastructure.

The electricity compositions for individual years are subsequently combined with the global energy scenarios to develop the EMFs for electricity. The derivation of the EMF follows Equation 4.6, with the only difference being that in this case the ecoinvent-matched EMFs for power generation units are used. In the further course of the evaluation, electricity also

Table 4.4: Further decomposition of individual energy sources for matching with the ecoinvent database

Generation type	ecoinvent description	Share	Reference
Nuclear	Pressure water reactor	21 %	[47]
	Boiling water reactor	79 %	
Solar (roof)	Monocrystalline modules	45 %	[47]
	Polycrystalline modules	55 %	
Wind onshore	Wind Turbine < 1 MW	7 %	[127]
	Wind Turbine 1–3 MW	68 %	
	Wind Turbine > 3 MW	25 %	

forms the basis for the EMFs of the other energy sources such as hydrogen via electrolysis, PtG or PtL.

Hydrogen For the two processes electrolysis and steam methane reforming (SMR), LCI data sets were taken from Bareiß et al. [128] and Antonini et al. [129]. Bareiß et al. describe a prospective proton-exchange-membrane (PEM) electrolyser with the previously noted efficiency η_{PtH_2}. Antonini et al. describe various hydrogen production technologies. For the present work, it is assumed that SMR technology is used for the production of hydrogen from natural gas, and thus, η_{SMR} applies. In contrast to SDA, the provision of natural gas is included here as explained in the next paragraph. The two publications show that the GHG emissions caused by the construction of the plant are very low compared to the operational emissions. Accordingly, no distinction is made in the number of full load hours (of the two processes) between scenarios and both systems run 5,000 h per year.

Gas As described previously, gas can be sourced as natural gas, biogas, domestically produced synthetic gas (PtG), or imported green methane. For the EMF of natural gas, the direct emissions of 201.6 g CO_2e/kWh are increased by the emissions throughout the upstream chain to 250.5 g CO_2e/kWh [130]. The direct emissions from the combustion of biogas are viewed as zero, analogous to the procedure for the SDA. Here, the emissions to be released are equal to those captured during the growing process. The upstream chain of biogas is set at 33.1 g CO_2/kWh [130], assuming the use of residues. For the PtG process, the methanation of Liebich et al. is used [131] whereby methanation requires hydrogen and CO_2. The hydrogen process is again taken from Bareiß et al. [128]. For the CO_2 supply, the Direct Air Capture (DAC) described by Deutz et al. is used [132]. Here, too, only the emissions in the upstream chain are accounted for and direct emissions are assessed as zero since their amount equals the amount of CO_2 captured in the supply process. Analogous to the processes for hydrogen supply, the full load hours are not altered between scenarios and are set to 5,000 h. For the import of green methane, the same methanation process is used and the production is carried out using solar energy in Morocco. In addition, the costs for the import via shipping transport are added with the help of the data from Pichlmaier et al. [133].

Liquid Fuels According to Figure 4.9, liquid fuels in the model are either oil-based, bio-based, electricity-based or imported green fuels. Analogous to the procedure for fossil gas, the direct emissions of fossil hydrocarbons of 266.4 g CO_2e/kWh are increased by the upstream chain to 301.3 g CO_2e/kWh [130]. In 2018, 29 % of biofuels in Germany were produced from rapeseed (102.1 g CO_2e/kWh), 3 % from sunflower (97.6 g CO_2e/kWh), 21 % from palm oil (69.5 g CO_2e/kWh), and 47 % from residues (24.7 g CO_2e/kWh) [130]. Therefore, the weighted average results in an EMF of 58.5 g CO_2e/kWh for the upstream chain. The PtL process is realised by FT synthesis. Again, hydrogen and CO_2 are used as inputs and accordingly derived from Bareiß et al. [128] and Deutz et al. [132]. Data from Liebich et al. is used for the construction of the FT plant [131] and the efficiency corresponds to that of SDA. For the import of green liquid fuels, the production again takes place in Morocco.

4.2.4 Life Cycle Inventory for Vehicle Types

Taking the process in Figure 4.11 into consideration, the procedure for deriving the conventional LCIs of vehicle types in Germany is now shown. Thereby, the LCIs contain all the material and energy flows between processes and the environment. The LCI described hereafter refers to all vehicle types that are part of the German transport fleet. All components of the LCIs in this thesis are based on the ecoinvent life cycle database (version 3.7.1) which contains inventories of around 18,000 processes [47] whereby the database distinguishes between different system models. First, a distinction is made between attributional and consequential LCA. Finnveden et al. defines the two types of LCA as follows [134]:

- Attributional LCA: LCA that aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems
- Consequential LCA: LCA that aims to describe how environmentally relevant flows will change in response to possible decisions

The choice of the form of LCA is thus directly related to the goal that is pursued. An attributional LCA asks which share of the total environmental impact belongs to the product while consequential LCA asks what consequences a product system has on the global environmental impact. Based on this, Ekvall derives the following distinction between the resulting assessments [135]:

- Attributional assessments give an estimate of what part of the global environmental burdens belongs to the study object
- Consequential assessments give an estimate of how the production and use of the study object affect the global environmental burdens

This study examines the influence on environmental impacts that can be attributed to the German transport sector. Accordingly, an attributional LCA is carried out.

The selection of the LCA system model in ecoinvent is further determined by the treatment of recycled products. Here, a distinction is made between the cutoff and the point-of-substitution approach, both of which are described in Figure 4.12. In the cutoff approach, secondary materials enter the upstream chain of a product without a burden and only the expenditure for recycling is to be attributed to the secondary use. Accordingly, the primary use does not receive any credit for recycling and only the expenditure for waste processing is reduced. This is in contrast to the point-of-substitution approach. Here, in the case of recycling, a credit is attributed to the primary use. The credit corresponds to the avoided burden that occurs due to the avoidance of primary material in the secondary use.

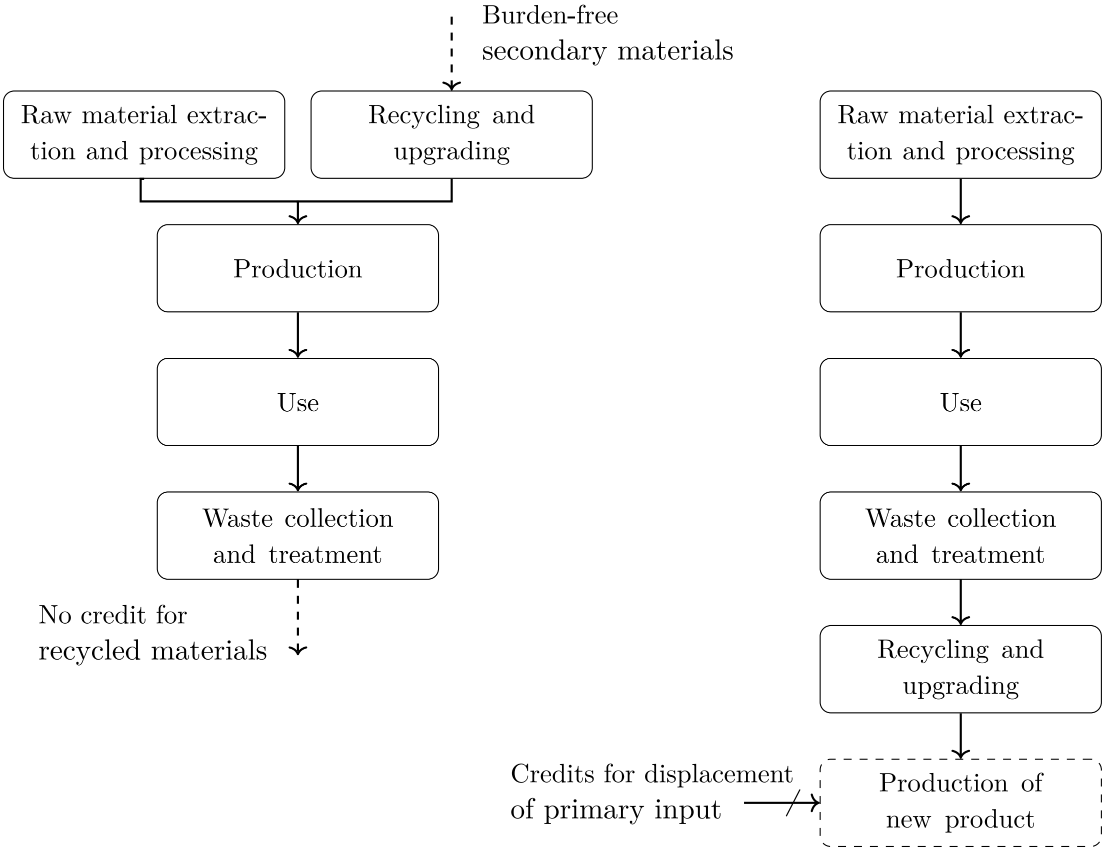


Figure 4.12: Explanation of the cut-off approach (left) and the point-of-substitution approach (right); own illustration based on [136]

Both systems are widely used in classical LCA. However, the point-of-substitution approach can lead to more complex results and thus the necessity of a profound explanation. While this is a manageable challenge for simple product LCAs, it is unsuitable for a broad, systemic approach as in the present work. The cutoff approach, on the other hand, represents the simpler alternative, which is thus better suited for systemic assessments. Consequently, the ecoinvent cutoff system model for attributional LCA is used in this thesis. With regard to the results, the cut-off approach leads to lower environmental impacts of the system with high proportions of secondary material inputs. On the other hand, the added value of possible recycling in the end-of-life phase is only given by the fact that no waste management has to be carried out. For the evaluation of the present system, it can be assumed that the environmental impact is lower than with the point-of-substitution approach.

Based on the selected ecoinvent system model, LCI databases are now derived for the years 2020, 2025, 2030, 2035, 2040, 2045, and 2050 and future processes are thereby adapted to reflect technological advancements. For example, assumptions are made for the future production of vehicles and their materials, which for example include the processes of manufacturing. In order to map the development of the production of road vehicles, i.e. cars, trucks, buses, and motorbikes, data from carculator is used. The open source tools carculator [124] and carculator-truck [125] contain data on the current and future production and disposal of vehicles as well as technical parameters such as service life and specific energy consumption. This extensive data is adapted to the German fleet with the help of the existing data as mentioned in Chapters 4.1.1 and 4.1.2 and various other sources [46, 137–142]. The other transport types were taken directly from ecoinvent and scaled according to their transport loads [47]. When combined, this results in conventional LCIs of the vehicle types in Germany (also see Figure 4.11).

4.2.5 Adjusting Background Data for the Scenarios

The conventional LCIs include future changes in the production and disposal processes of the vehicles, but no changes to the energy supply. To better reflect the future energy supply, the corresponding background data and thus the entire ecoinvent database is adjusted and the model environment PRospective EnvironMental Impact AsSEssment (premise) is used to implement the adaptation of the database. The PRospective EnvironMental Impact AsSEssment (premise) model environment is an open source model by Sacchi et al. [49] that allows researchers to integrate the results of scenarios from the IAM model REMIND introduced in Chapter 3.3 into the ecoinvent database. Global geographically resolved data from the REMIND scenarios is taken for primary, secondary, and useful energy demand by energy source, technology, and application. Thereby, the model contains up to 21 regions that can be distinguished and integrated into the LCA model. The years 2020 to 2050 are mapped in ten-year steps and adaptations can be developments of existing processes (e.g. with regard to efficiency) or adding completely new processes. In places where the IAM model does not provide sufficient data, other sources are used. Thus, the libraries carculator [124] and carculator-truck [125] are also used with regard to possible transport options (also see Chapter 4.2.4). The schematic modelling approach used in this dissertation is described in Figure 4.13.

The REMIND and ISAaR models shown in the illustration are two models that contain developments of the energy supply. REMIND covers the entire earth with low spatial resolution, while ISAaR covers Europe with high resolution. To improve the consistency between the two models, data from ISAaR rather than REMIND is used for the European region. With

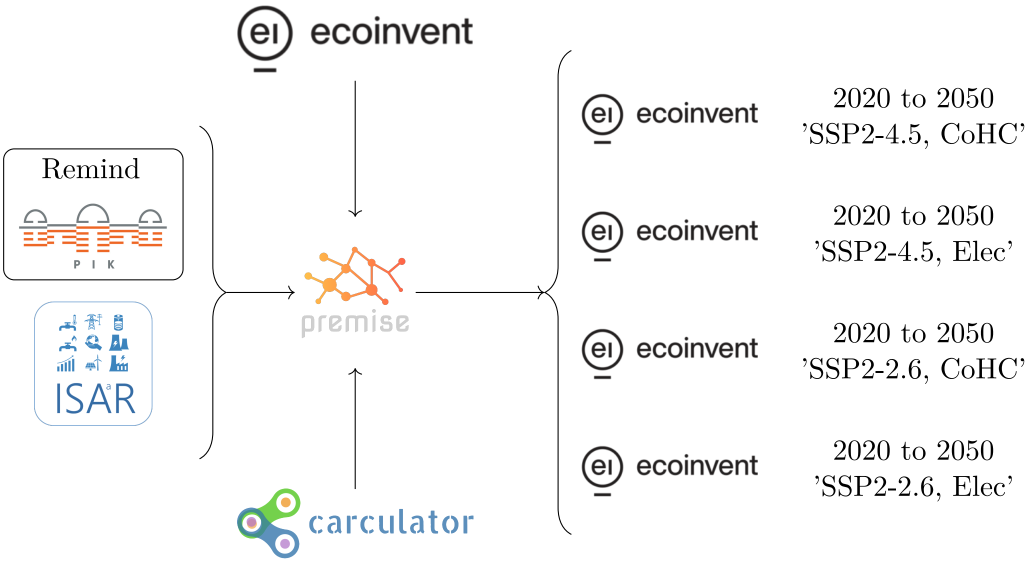


Figure 4.13: Modelling approach to adapt the ecoinvent database using the IAM model Remind and the energy system model ISAaR with the help of premise; schematic representation after Sacchi et al. [49]

the help of premise, the ecoinvent database is subsequently adapted according to the selected scenarios and the two scenarios Elec and CoHC for European development are matched with the two scenarios for global development SSP2-2.6 and SSP2-4.5. At this point, the Trend mobility scenarios are used (also see Chapter 3.3.1) and a distinction between Trend and Multi is not made. Since the results differ only slightly in terms of energy supply (also see Chapter 5.1.3), the resulting error is considered insignificant.

4.2.6 Impact Assessment

While common LCA studies cover a wide range of environmental impact categories, this dissertation focuses on the assessment of climate change whereby the increase in radiative forcing is used to quantify impacts in this category. It is directly influenced by the concentration of GHG in the atmosphere [126]. The indicator developed for determining the impact on the category of climate change is the global warming potential (GWP). For this, two characterisation models with different time horizons of 20 and 100 years are available. The use of the time horizon of 100 years is common. For example, the Conference of Parties 2019 (COP24) adopted this as the methodology in its reporting [143]. The most important GHGs are carbon dioxide, methane, and nitrous oxides. In 2020, carbon dioxide was responsible for 74.4 %, methane for 17.3 %, and nitrous oxides for another 6.2 % of greenhouse gases [2]. The characterisation factors for these three gases (given in the IPCC Fifth Assessment Report) are shown in Table 4.5 for both the hundred- and twenty-year time horizons [126].

Table 4.5: Characterization factors of the three main GHGs in kg CO_2e per kg gas [126]

Assessment Method	**Carbon Dioxide**	**Methane**	**Nitrous Oxide**
IPCC 2013, GWP 100a	1	29.7	264.8
IPCC 2013, GWP 20a	1	84.6	263.7

As shown, the main difference between the two methods lies in the valuation of methane and thus the relevance of the respective assessment method is high in those sectors that produce a lot of methane (e.g. agriculture). In the present case of the assessment of the German transport sector, the relevance is considered low which is why only the method with a time horizon of 100 years is used.

4.3 Preliminary Summary

Based on the scenario development in the previous chapter, and as a basis for the results that follow, the chapter describes the modelling approach and the assumptions made.

Thereby, the model of the German transport sector TraM was presented, which depicts scenarios for the transport sector. With the help of input values for transport demand per mode of transport, the model is able to calculate future fleets. The fleet is then designed in such a way that it is able to cover the transport demand of the respective mode of transport. The matrix representation of the fleet, which records which vehicle types are registered and decommissioned each year, enables monitoring of the entire development across the scenarios. Based on this, and with the help of a broadly researched data basis, energy requirements are subsequently assigned to each vehicle type and are then combined with load profiles. The resulting temporally resolved energy demands are finally transferred to an energy system model which delivers emission factors in return.

The derivation of the emission factors for energy carriers in the two evaluation methods SDA and SDLCA were explained. The results include emission factors for electricity, hydrogen, gas, and liquid fuels. They contain the response of the energy supply model to energy consumption whereby the required energy is supplied based on an economic optimisation approach.

Furthermore, the extension to include the life cycle perspective was outlined. In addition to the expansion of the emission factors for energy sources to a life cycle perspective, this also includes the production and disposal of vehicles. For this purpose, a model environment was developed that makes it possible to adapt ecoinvent data based on existing databases. This was done with a focus on the German transport sector. The modelling also includes the adaptation of background data with regard to the future energy supply in operation as well as in the upstream and downstream chains.

5 Results and Assessment

Based on the scenarios described in Chapter 3 and using the methodology from Chapter 4, the results are now deduced in the following. First, the general results of the scenario modelling are presented in Section 5.1. This forms the basis for the subsequent ecological assessment. Consequently, in Chapter 5.2, the results of the System-Dynamic Assessment (SDA) are discussed. Finally, Chapter 5.3 shows the results of the System-Dynamic Life Cycle Assessment (SDLCA).

5.1 Scenario Results

The following explanations contain the general results of the scenario modelling which are identical for both assessment methods. They contain the development of the fleet size and its composition, the associated energy demand, and the energy generation required for this.

5.1.1 Fleet Development

As described in Section 4.1.1, the necessary fleets are determined on the basis of the transport demand and the development of annual mileage and capacity utilisation. The development of transport demand differs in the two scenarios Trend and Multi. In addition, two technology scenarios are distinguished with CoHC and Elec, and thus a total of four transport scenarios are examined. As shown in Tables 3.4 and 3.5, the largest transport demands are for private cars in passenger transport and for semi-trailers in freight transport. In addition, in the Multi scenario, shared cars and, in both scenarios, LDVs experience a very large increase. Therefore, these transport types will now be discussed in the course of the fleet evaluations.

Car Fleet At the beginning of the period under consideration, the model calculates a passenger car stock of 45.5 million passenger cars. This is 0.45 % lower than the number of vehicles actually registered all year round in 2020 [64]. Of this total fleet, 60.5 % are petrol-ICEVs, 36.2 % diesel-ICEVss, 0.9 % CNG-ICEVs, 1.2 % HEV, 0.7 % BEV and 0.5 % PHEV. Although the absolute number of privately owned cars is decreasing in all four scenarios, the subsequent developments of the fleets are very different. These developments are shown in Figure 5.1.

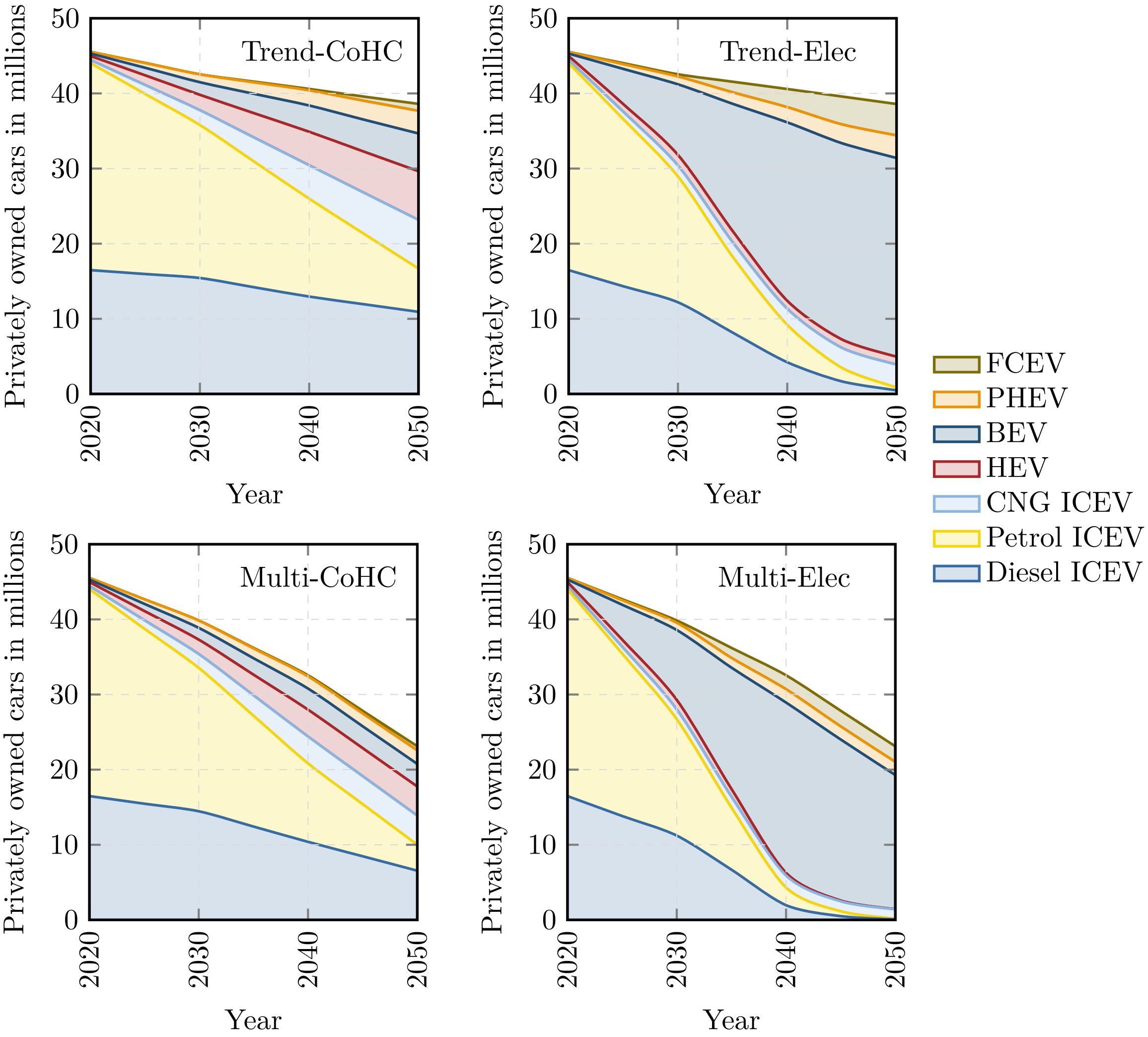


Figure 5.1: Development of technologies in the privately owned car fleet of the scenario Trend-CoHC (top left), Trend-Elec (top right), Multi-CoHC (bottom left), and Multi-Elec (bottom right)

The Trend-CoHC scenario has the most moderate changes in the fleet. With regard to the conventional energy carriers petrol and diesel, the stock figures of the corresponding ICEVs decrease, but there is still a considerable number of vehicles in the system until the end of the period under consideration in 2050. On the side of alternative drives, the CNG-ICEVs and HEVs, in particular, are increasing. Only 13.0 % of BEVs, 7.8 PHEVs, and 2.4 FCEVs are in the passenger car stock in 2050. In its multimodal counterpart Multi-CoHC, by 2050 the number of privately owned cars decreases by 49.2 % to 23.7 million cars. At this point, it must be mentioned that in this scenario, in addition to an extremely strong development towards car sharing vehicles, public transport means such as buses and especially trains also increase strongly. In Multi-CoHC, the new registration shares of the individual technologies in the years are equal to those of the Trend-Elec scenario and, accordingly, the stock shares develop almost identically. The main difference compared to Trend-CoHC is that the number of decommissionings is much higher than the number of new registrations. Nevertheless, this has a negligible effect because the technology composition of the decommissionings does not differ too much compared to the new registrations in each year because of a relatively slow technology transition.

This is different for the electrification scenarios Trend-Elec and Multi-Elec. Here, the transformation speed towards alternative drive technologies is very fast. In the Trend-Elec scenario, 22.1 % and thus 9.4 million vehicles are already BEVs in 2030. By 2050, the number further increases to 26.4 million vehicles and a share of 68.5 % of the total fleet. In the target year, conventional petrol ICEVs and diesel ICEVs have been reduced to a combined share of 2.3 %. A further 7.9 % of vehicles are powered by CNG and 2.7 % are HEVs. In the area of electrified vehicles, in the fleet a further 7.8 % are PHEVs and 10.8 % are FCEVs. Analogous to Multi-CoHC, the change to a more multimodal transport system also leads to a drastic reduction in the number of vehicles in the Multi-Elec scenario. In addition, the rapid technological change contributes to an even higher share of electric vehicles in 2050 with 77.2 BEVs.

As already explained, the steep increase in the use of car sharing is partly responsible for the significant reduction in the number of cars in the multimodal scenarios. In order to be able to classify the size of the corresponding fleets and also to put them in relation to those of privately owned cars, Figure 5.2 shows the number of shared cars for both mobility scenarios. According to the explanations in Chapter 3.3.1, there is no variation in the technology scenarios, as the current fleet and the anticipated development already contain very high shares of alternative drive systems, especially BEVs.

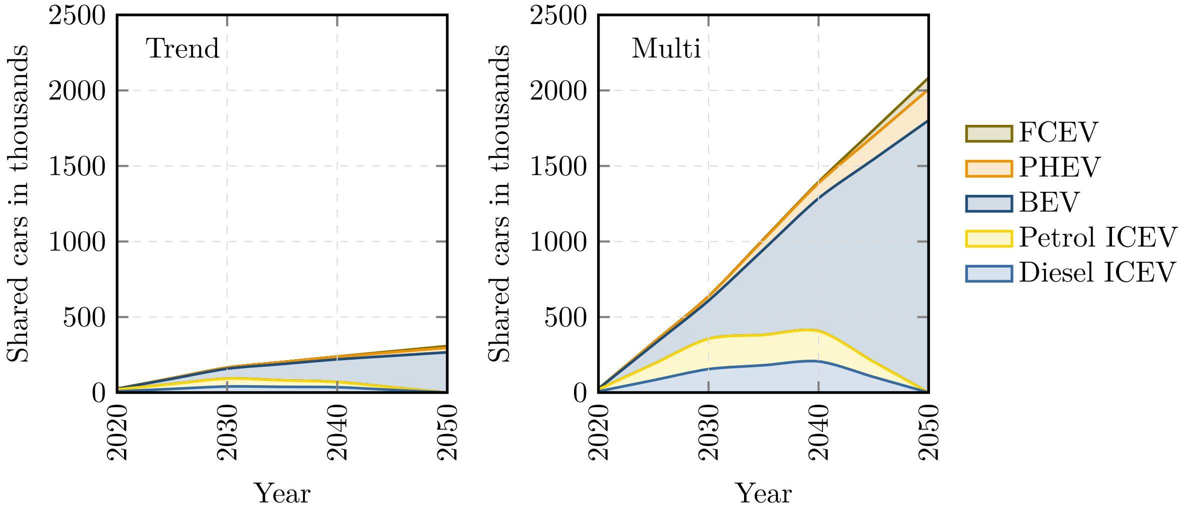


Figure 5.2: Development of technologies in the shared car fleet in both scenarios resulting from the mobility scenario Trend (left) and both scenarios resulting from the mobility scenario Multi (right)

Starting in 2020, the car sharing fleet will have 25,400 vehicles. In the conventional mobility scenarios, the number increases slowly. Thus, in Trend-CoHC and Trend-Elec, there are slightly more than 300,000 shared vehicles in the fleet in 2050. These consist of 86.5 % BEVs, 9.8 % PHEVs, and 3.7 % FCEVs. The same proportions with a much higher number are found in 2050 in the fleet of shared cars in the scenarios Multi-Elec and Multi-CoHC. Here, the number increases to 2.1 million vehicles. The shared vehicles can cover a higher transport performance than privately owned cars. The number of privately owned cars N_{pc} that can be replaced by the number of shared cars N_{sc} in this respect is as follows:

$$N_{pc} = N_{sc} \cdot \frac{cf_{sc}}{cf_{pc}} \cdot \frac{m_{sc}}{m_{pc}}, \tag{5.1}$$

where:

cf_{pc}, cf_{sc} — Capacity factors of privately owned and shared cars

m_{pc}, m_{sc} — Annual mileages of privately owned and shared cars

With the given annual mileage of 13,953 km for private cars and 28,000 km for shared cars and utilisation rates of 1.5 and 2.0 pkm/km, respectively, this results in 5.6 million replaceable private vehicles. As private vehicles decrease to a greater extent in the scenarios Multi-CoHC and Multi-Elec, the corresponding missing transport performances have to be covered by public transport.

Light Duty Vehicle and Semi-Trailer Fleet In the area of commercial vehicles, special attention is paid to LDVs and semi-trailers. In accordance with the explanations in Chapter 3.3.1, no distinctions are made with regard to mobility in the scenarios. LDVs are used in delivery traffic in particular. In this sector, transport performance is believed to strongly increase, and thus the number of LDVs also increases. Figure 5.3 illustrates the developments in the fleets of the two technology scenarios.

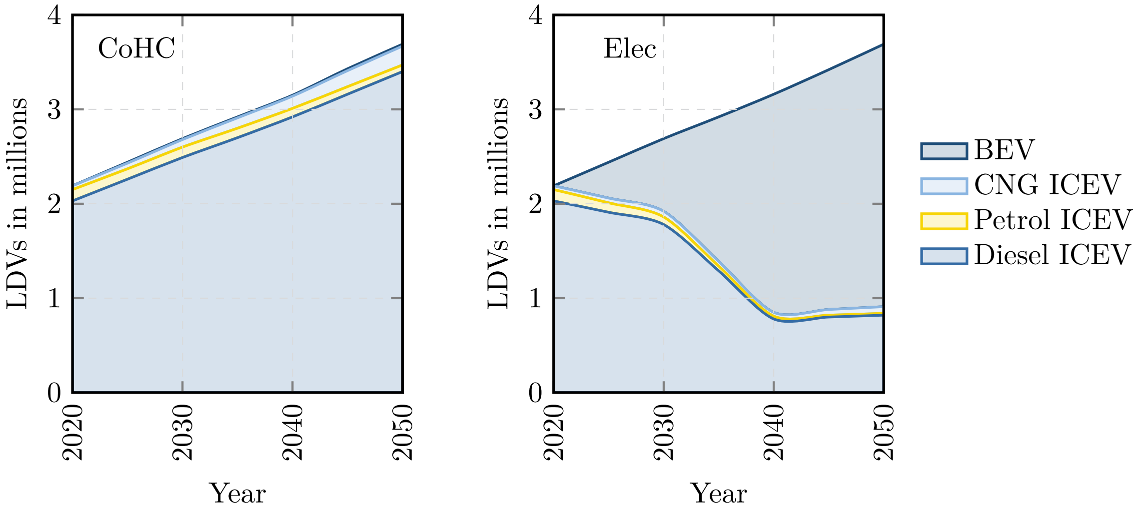


Figure 5.3: Development of technologies in the LDV fleet in both scenarios resulting from the technology scenario CoHC (left) and both scenarios resulting from the technology scenario Elec (right)

While there will be 2.2 million vehicles in the fleet in 2020, the number will increase to 3.7 million vehicles by 2050. In the conventional technology scenarios Trend-CoHC and Multi-CoHC, these vehicles are almost exclusively powered by diesel in the target year whereas in the electrification scenarios, a switch to mainly BEVs takes place. In this case, the number of electrified LDVs steadily increases up to 2.8 million units in 2050 and a further 0.8 million vehicles continue to run on diesel. The rest are divided between CNG ICEVs and petrol ICEVs.

In the semi-trailer sector, transport performances and thus vehicle numbers also increase slightly over time. In the period under consideration, the number of vehicles increases by 10.0 % to 194,062 vehicles (Figure 5.4).

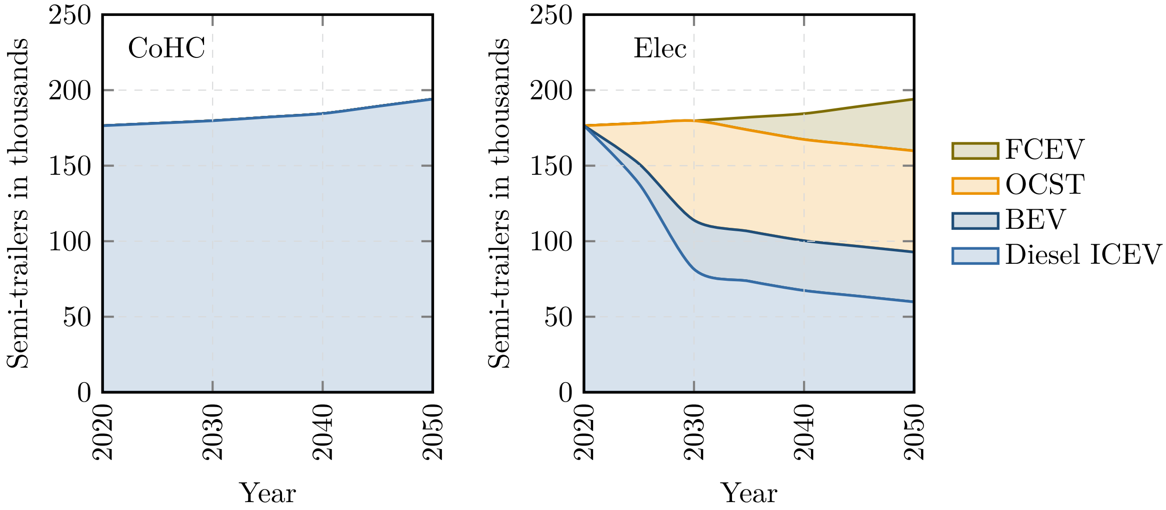


Figure 5.4: Development of technologies in the semi-trailer fleet in both scenarios resulting from the technology scenario CoHC (left) and both scenarios resulting from the technology scenario Elec (right)

In the Trend-CoHC and Multi-CoHC scenarios, these are powered by diesel over the entire period under consideration. In contrast, electrification takes place in part in the other two scenarios Trend-Elec and Multi-Elec. Thus, the shares in the stock of BEVs, OCSTs, and FCEVs increase strongly, especially in the years before 2030. Although the shares of alternative technologies continue to increase over the course of time, this increase is no longer as rapid. Finally, for 2050, the propulsion mix contains 30.8 % diesel ICEVs, 17.0 % BEVs, 34.5 % OCSTs, and 17.7 % FCEVs. This rapid transformation is possible due to very short lifetimes of 6 years. The expansion of corresponding infrastructure, especially in the case of OCSTs, is thereby assumed and taken into account in later analyses of the costs as well as the ecological analysis in the course of SDLCA.

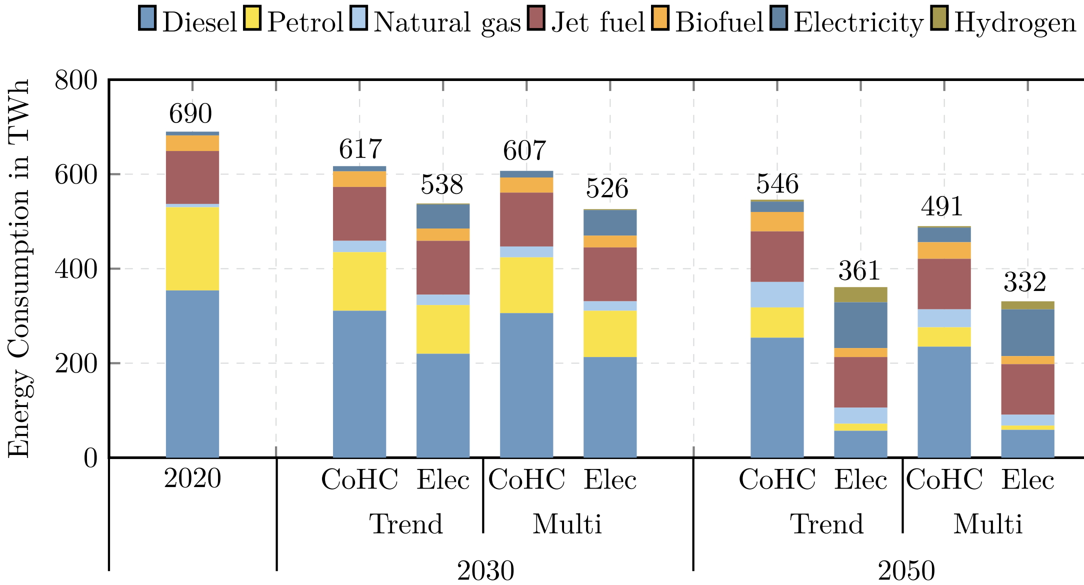


Figure 5.5: Energy demand per energy carrier for each scenario

5.1.2 Energy Demand

The fleet developments described above are the basis for the development of energy consumption. To obtain these, the number of vehicles per transport type is combined with the annual mileage and the specific consumption. The result of the energy consumption per energy carrier for the years 2020, 2030, and 2050 are shown in Figure 5.5.

According to the model, 690.0 TWh will be needed in the transport sector in 2020. Compared to the figures of the AG Energiebilanzen, this is 9.1 % less than in 2019 and 8.4 % more than in 2020 [144]. At this stage, however, it is important to highlight the nature of the accounting. On the one hand, the AG Energiebilanzen uses a top-down approach to divide the energy deliveries. On the other hand, the model is based on a bottom-up approach arising from the vehicles and their energy demand. The main differences that arise in this context are due to international journeys and tank tourism in border regions (also see Chapter 6.1) as, especially in road freight transport, this can lead to deviations. In 2020, this will mainly involve the use of hydrocarbons in transport. With 354.0 TWh, diesel is the most important energy carrier in transport as it is used in both passenger transport (181.3 TWh) and in freight transport (165.4 TWh). Furthermore diesel powers trains (4.0 TWh) and vessels (3.4 TWh). Besides diesel, petrol with 176.4 TWh and paraffin with 112.2 TWh are important energy carriers in transport. Electricity will only play a minor role in 2020 as it will only be used in train transport in noticeable quantities of 8 TWh. The future energy consumption of transport is lower than that of 2020 in all scenarios. Since the absolute transport performance remains the same or even increases, it is evident that this is due to the more efficient use of transport modes. When comparing the two technology variants CoHC and Elec, it becomes clear that the use of electrified road vehicles such as BEVs, PHEVs, and FCEVs can lead to a significant decrease in energy consumption. The Elec scenarios always have a lower energy demand in 2050 than their conventional counterpart CoHC as their consumption of hydrocarbons decreases while their consumption of electricity and hydrogen increases. Due to the more efficient technologies, the total consumption decreases. This change takes place only partially in the CoHC.

Furthermore, the scenario comparison between Trend and Multi shows the lower energy demands of the multimodal scenarios. Thus, multimodal transport use leads to a reduction of 10.0 % in energy demand in the CoHC scenarios and 8.0 % in the Elec scenarios. The lower energy consumption is partly attributable to the fact that more car kilometres are travelled electrically due to a higher electrified share of the shared fleet. In addition, more energy-efficient means of transport such as buses and trains are being used. In order to gain a feeling for the modes of transport and their consumption and at the same time to be able to compare the scenarios in this respect, Figure 5.6 shows the requirements in detail.

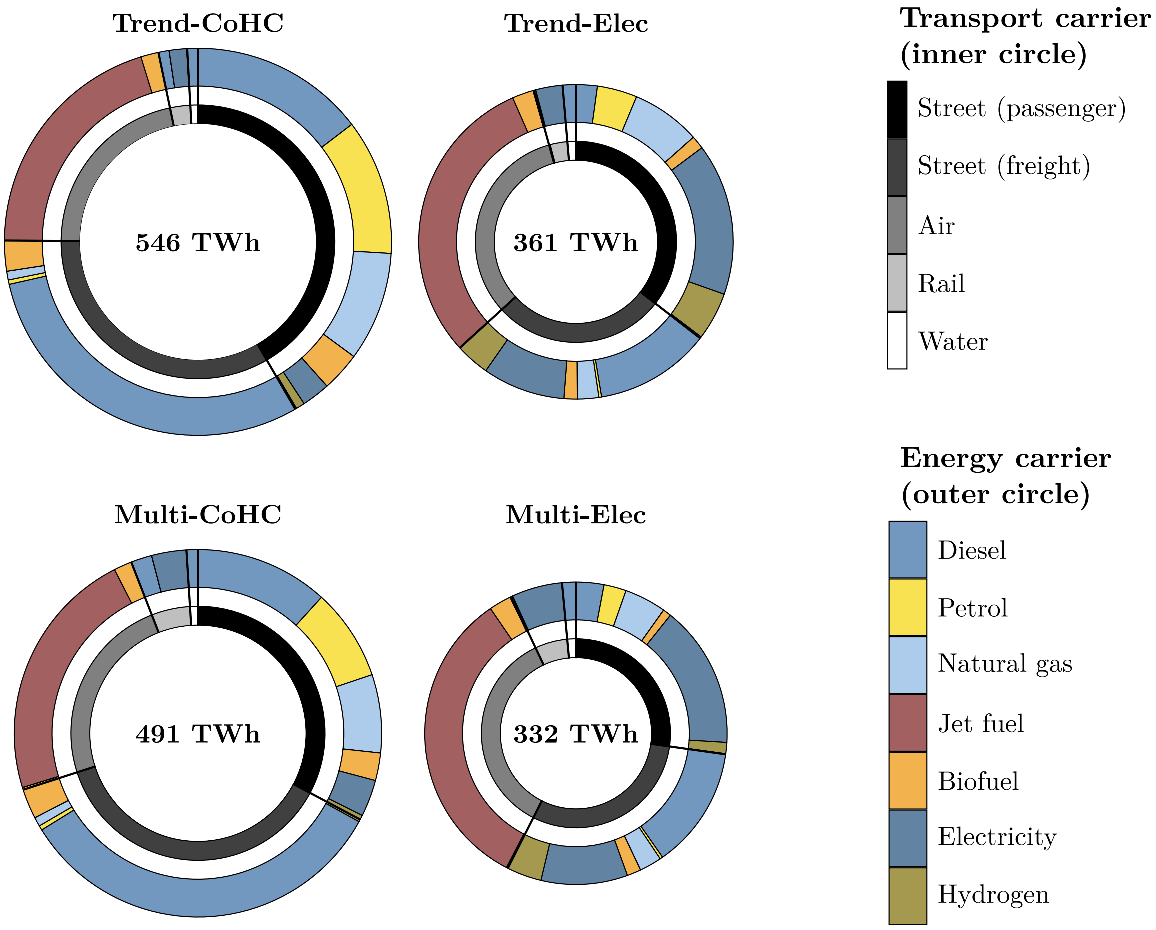


Figure 5.6: The energy demand in 2050 of the four scenarios distributed according to transport carriers (inner circle) and energy carriers (outer circle); the total energy demand corresponds to the area within the edge of the outer circle

The diagram shows that road traffic will continue to play a major role in future energy consumption. Even in the Elec scenarios, in which large parts of road traffic are electrified and in Multi-Elec in which traffic shifting also takes place, the highest energy consumption is in road traffic. No major changes take place in the area of air traffic as jet fuel will continue to be used exclusively in 2050. The same applies to shipping and diesel. By definition, the energy consumption of rail traffic increases in the Multi scenarios. However, as described above, this increase is more than compensated by the decrease in energy consumption in road transport. In the Elec scenarios, more train routes are also electrified and trains are equipped with batteries. This leads to a decrease in diesel and an increase in electricity for trains.

In order to provide energy in the sense of the model landscape used, a time-resolved approach to energy consumption for electricity and gases is necessary. As described in Chapter 4.1.3, the time resolution of the gases methane and hydrogen is 1 day. However, as already shown in Conrad et al. the time resolution of gases from the transport sector is of secondary relevance for the design of the energy sector. Thus, in the following, specifically the resulting electricity loads will now be discussed. This will take a look at short-term as well as seasonal dependency. In this context, Figure 5.7 shows the monthly power requirements and the annual duration line of the hourly values.

Monthly electricity demands exhibit a seasonal dependency. Thus, it can be seen that in 2020 – and for the conventional technology scenarios CoHC in 2050 – there are no major differences between the summer and winter months. These three data series are each strongly dominated by the electricity load induced by trains and do not show seasonal differences. Although electricity consumption by cars increases in the CoHC scenarios by 2050, the demand in June is only 338 GWh (Trend-CoHC) respectively 290 GWh (Multi-CoHC) lower than in January. This is due to the fact that June is the warmest and January the coldest month of the weather year that is considered. The situation is different in the Elec scenarios as, in addition to the generally higher demand, a strong dependence on temperature is evident here which is due to the higher electricity demand from electric vehicles in winter. In this case, the energy demand in June is 1,616 GWh (Trend-Elec) respectively 1,341 GWh (Multi-Elec) higher than in January. In both technology variants, the seasonal dependency is weakened in the multimodal scenarios, since more trains and fewer cars are used.

The annual duration line of hourly values illustrates a greater fluctuating electricity demand in the progressive technology scenarios. The curve, in which the hourly values of the year are ordered according to their size, on the one hand shows the maximum loads that occur within a year. The scenario Trend-Elec, for example, has the highest hourly load of all scenarios at 28.2 GW. This is 10.7 % higher than the maximum load of the Multi-Elec scenario, which has the highest electricity demand with 99.4 TWh. Again, the mitigating effect of electric public transportation is evident. The steepness of the curve also represents the differences in the load. This is much more pronounced in the electrification scenarios than in the conventional technology scenarios. When exclusively looking at the electricity load, it can be assumed that

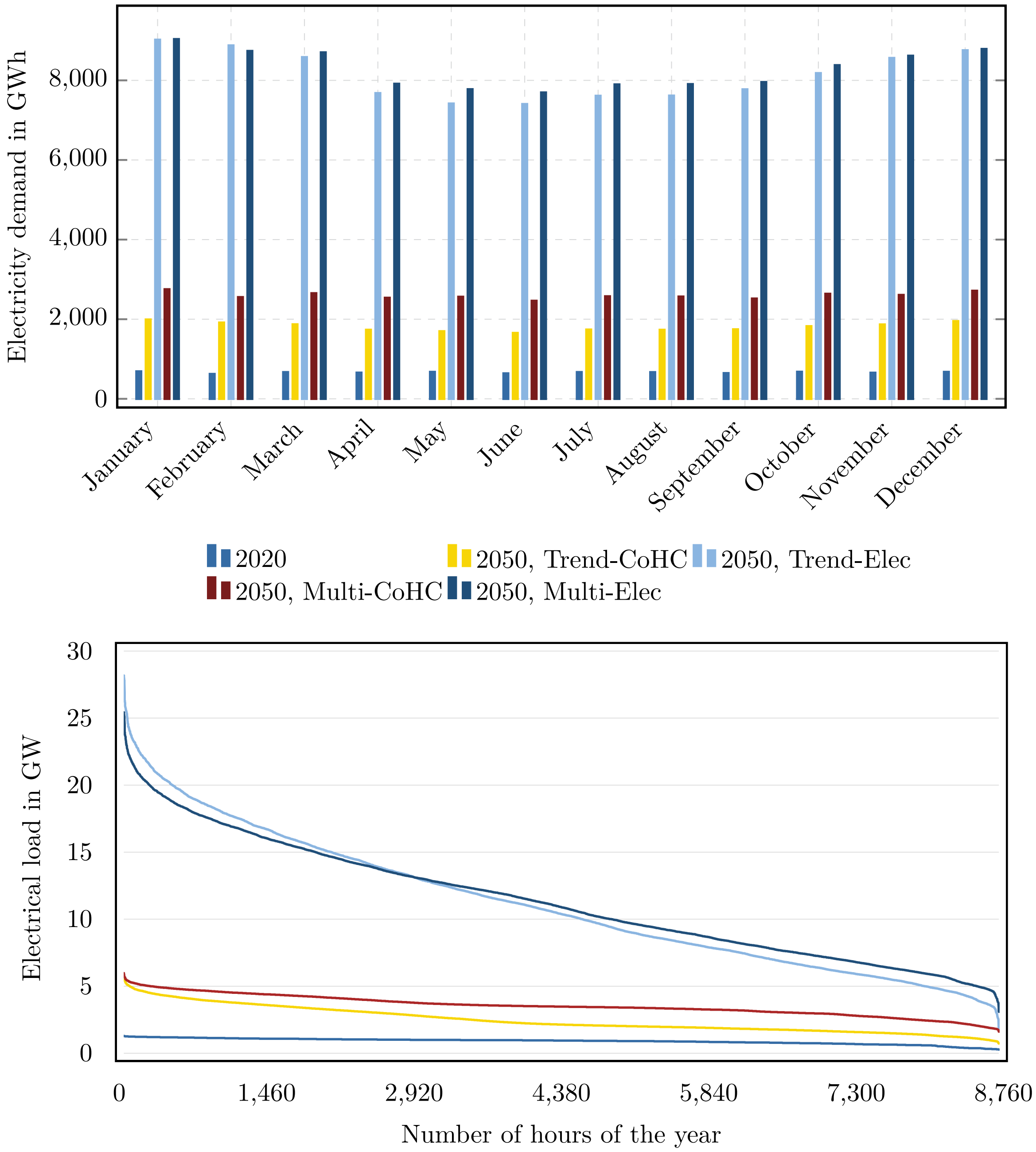


Figure 5.7: Electricity demand (top) and annual duration curve of electrical load (bottom) in 2020 and in all three scenarios in 2050

the stress on the energy supply system is higher in the progressive technology scenarios. This hypothesis will be investigated in the following chapter.

5.1.3 Energy Supply

The energy supply sector is simulated for the whole of Europe using the ISAaR model (also see Chapter 4.1.3). At the European level, the set GHG emission reduction targets of -

55 % by 2030 and -95 % by 2050 compared to 1990 must be met. The emission cap for 2040 results from the mean value of 2030 and 2050. This results in GHG emission caps of 2.589 Mt CO_2, 1.439 Mt CO_2 and 288 Mt CO_2 for the years 2030, 2040, and 2050. Thereby, Europe includes the 27 countries of the EU as well as the United Kingdom, Switzerland, and Norway (EU27+3). Figure 5.8 depicts the total GHG emissions in these countries.

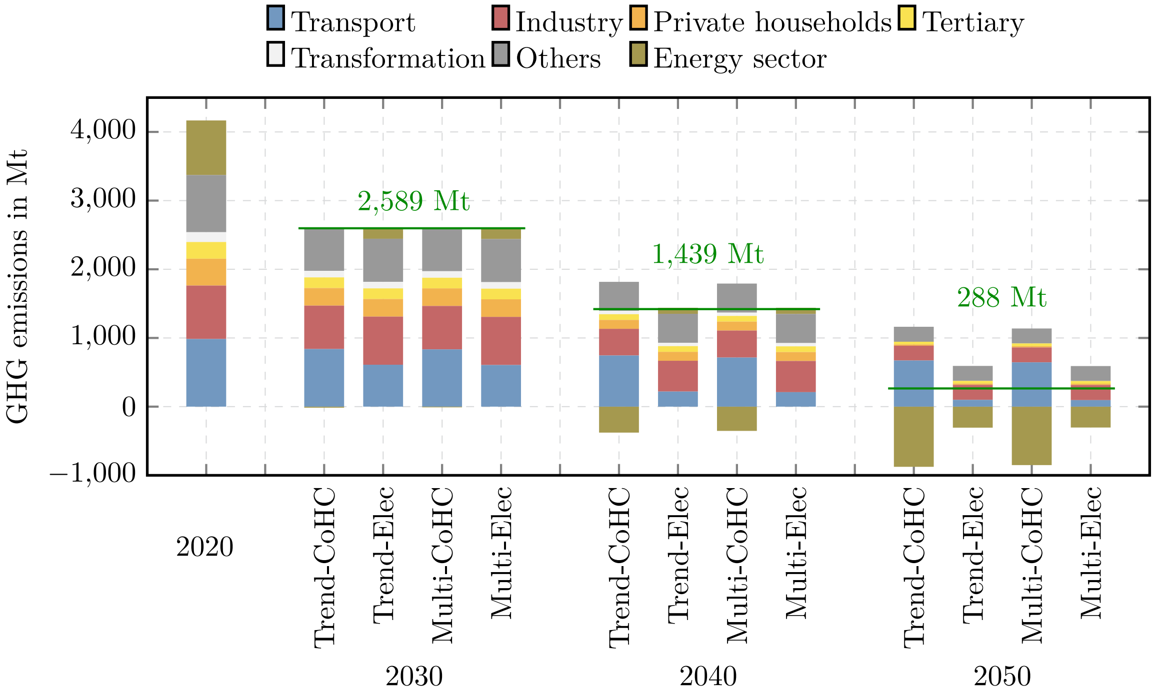


Figure 5.8: Total GHG emissions of the EU27+3 by sector including the European emission cap; here, emissions of synthetic fuels such as PtG and PtL are counted positively in the application sectors and negatively in the energy sector

The graph shows that in each year and each scenario, the emission limit is reached. This means that, according to the linear optimisation model, no more cost-effective system with less emissions is possible. With regard to the allocation of GHG emissions, it should be mentioned that the emissions are accounted for where they occur. Thus, synthetic fuels are accounted for as positive emissions in the application sectors and as negative emissions in the supply sector. The sectors private households, tertiary, transformation (e.g. refineries), and others (e.g. agriculture) reduce their emissions equally in all scenarios according to the solidEU scenario in the eXtremOS project [8].

The highlighted emissions from the transport sector depend on how many hydrocarbons are combusted in the sector. The same is basically the case for the industrial sector with the addition of process emissions. However, the energy supply sector has the possibility to make use of the CO_2 capture potentials of the industry, which leads to different amounts of GHG emissions in the industry in the scenarios. The main degree of freedom to reach the emission cap lies in the supply sector, which shows significant differences between the scenarios.

In the CoHC scenarios, large amounts of emissions will continue to be released in the European transport sector in future years. In Trend CoHC, GHG emissions in the European transport sector decrease from 985 Mt CO_2e in 2020 to 839 Mt CO_2e in 2030 and to 672 Mt CO_2e in 2050. In order to stay below the emission cap, the supply sector already has to compensate 15 Mt CO_2e from the other sectors in 2030. By 2050, the emissions compensations of the supply sector must increase to 876 Mt CO_2e. This is achieved by capturing CO_2 as well as producing and importing synthetic methane and liquid hydrocarbons. The same orders of magnitude are also recorded for the Multi-CoHC scenario. Here, with 4.0 %, the GHG emissions of the transport sector in 2050 in the EU27+3 are only insignificantly lower than in Trend-CoHC. Thus, the supply sector behaves similarly in this scenario.

The situation is different for the Elec scenarios. Here, due to the strongly increasing use of electricity and hydrogen in road transport, gradually fewer GHG emissions are emitted. In the Trend-Elec scenario, the European transport sector emits 610 Mt CO_2e in 2030, 220 Mt CO_2e in 2040, and 99 Mt CO_2e in 2050. This leads to lower pressure on the energy supply sector, which still has positive emissions of 145 Mt CO_2e respectively 87 Mt CO_2e in 2030 and 2040. In 2050, the emissions of the supply sector are also negative in this scenario with -306 Mt CO_2e. In this case, too, the multimodal scenario leads to only a minor difference. At 4.0 % in 2050, the relative reduction in emissions in Multi-Elec compared to Trend-Elec is exactly the same as in the CoHC scenarios.

In the following, the focus is now turned to Germany, as national emission factors are to be derived for the present assessment. For this purpose, it is of particular relevance how the energy carriers electricity, gas, liquid hydrocarbons, and hydrogen are provided. Figure 5.9 shows the shares of supply options for all four scenarios over the period under consideration.

In all scenarios, a rapid shift in the German electricity generation towards renewables is discernible and the shares of these are already between 92.8 % and 98.2 % in 2030. Here, again, the higher values are recorded in the CoHC scenarios. From the consistently high shares of renewable electricity generation in 2030, it can be derived that this is the most cost-effective option for saving emissions accordingly. Thermal power plants with coal or gas are only used in Germany to a very small extent at peak load times. In terms of import balance, Germany is changing from an exporter to an importer of electricity. The resulting import balance ranges from 35.8 TWh in Multi-Elec to 48.4 TWh in Trend-CoHC. However, with a total electricity demand of 897 TWh and 971 TWh respectively, this can be classified as low. The subsequent changes in German electricity generation are only minor and the renewable share in electricity generation in the scenarios converge in a range between 96.6 % and 96.9 % by 2050. The decrease in the share in the CoHC scenarios is due to the increasing electricity demand. The remaining capacities of gas-fired thermal power plants for peak load coverage are needed in all scenarios.

Interesting differences emerge when comparing the provision of the energy carriers gas and liquid hydrocarbons. In the CoHC scenarios, large quantities of green liquid hydrocarbons are

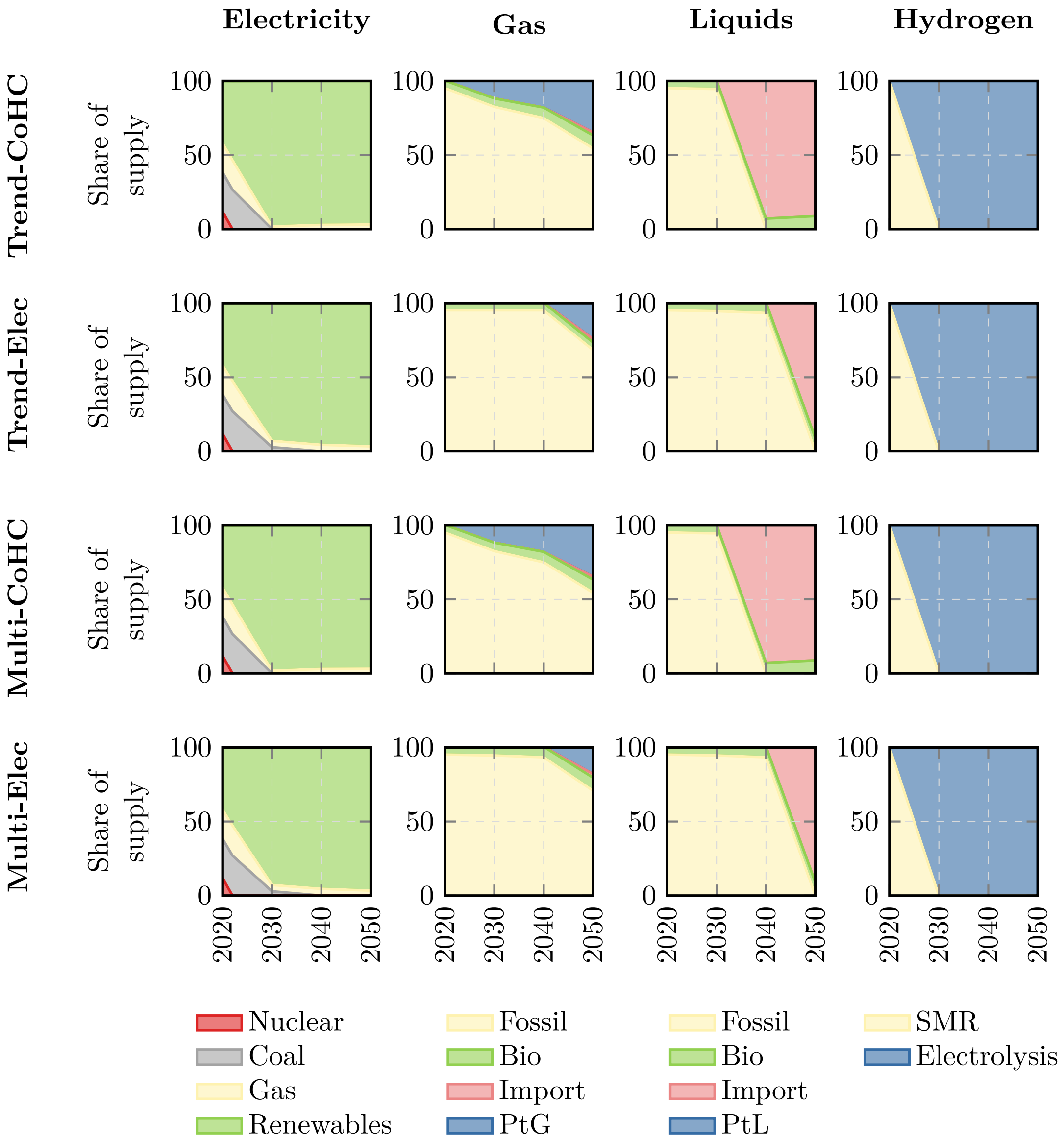


Figure 5.9: Supply shares for the energy carriers electricity, hydrogen, gas, and liquid hydrocarbons in Germany in all four scenarios; the legend for each energy carrier is shown beneath the column

imported as early as 2030, and by 2040 the supply is completely changed compared to the years before, in which the energy carrier was almost exclusively obtained from fossil sources. In the Elec scenarios, this change occurs a decade later. With regard to the energy carrier gas, such a complete change does not take place. Although methanation is used as a PtG technology, especially in the CoHC scenarios, most of the gas that is provided will still be of fossil origin in 2050. Both the import of green, carbon-based energy carriers and their domestic production with electricity are considered negative emission options. As discussed in Conrad et al. [9], the choice of the negative emission option is strongly related to the underlying cost assumptions. Due to the fact that these technologies have not often been implemented, the assumptions are subject to large uncertainties and thus a conclusion regarding which technology should be favoured in this context can therefore not be made.

In all scenarios, the hydrogen supply in Germany is completely converted to electrolysis between the years 2020 and 2030. The demand in 2030 ranges between 53.5 TWh in Trend-CoHC and 68.8 TWh in Trend-Elec. By 2050, this range increases from 220.1 TWh to 247.6 TWh.

5.1.4 Preliminary Summary

In the course of this section, the basic scenario results were presented. According to the underlying methodology, the results of fleet development, energy consumption, and energy supply were discussed.

Fleet development The results of the various scenarios make it clear that, in theory, a technology shift in road transport can be implemented quickly. This is due to the comparatively short service lifetimes in all areas of road transport in Germany. The recorded multimodal scenarios are also capable of greatly reducing the absolute number of vehicles. This is achieved through the increased use of car sharing vehicles, which are well embedded in an overall strongly multimodal environment.

Energy Demand At 80.8 % in 2020, the majority of energy consumption is attributable to road transport and of this, 68.3 % is in passenger transport. Across all modes of transport, diesel is currently the most important energy carrier in the transport sector with 51.1 %. The use of more efficient technologies reduces energy consumption in all scenarios. In the Elec scenarios, this reduction is much more pronounced. While in the CoHC scenarios, energy demand decreases by 20.9 % and 29.0 % respectively from 2020 to 2050, it declines by 47.7 % and 52.0 % respectively in the Elec scenarios. However, the greater use of electricity in the scenarios also leads to higher fluctuations in the electricity load. This in turn can cause more stress on the energy supply system although multimodality can lead to a smoothing here as well. While the Multi-Elec scenario produces the highest annual energy demand, the hours with the highest power demands are found in the Trend-Elec scenario.

Energy Supply Greater than the impact caused by the higher electricity loads is the impact caused by the emissions to be avoided in the energy supply sector. In all scenarios, there is a strong expansion of renewable energies between 2020 and 2030. The import of liquid hydrocarbons in the CoHC scenarios changes between 2030 and 2040 from fossil carriers to electricity-based fuels, whereas in the Elec scenarios, this takes place a decade later. In all scenarios, the supply of hydrogen from 2030 onwards is 100 % derived from electrolysis. These shares now form the basis for the emission factors to be developed in Chapters 5.2 and 5.3.

5.2 System-Dynamic Assessment

The results presented in the following section are derived from the SDA approach. To enable the evaluation of the scenarios, the emissions and the costs due to the supply of the demanded energy carriers are discussed in Chapter 5.2.1. Subsequently, the GHG emissions are evaluated in Chapter 5.2.2 before a cost perspective is added in Chapter 5.2.3.

5.2.1 Emission Factors and Energy Costs

To further derive the total emissions in the course of the SDA, EMFs are assigned to each energy carrier used in the transport sector. The EMFs contain the direct emissions due to the combustion of gas and liquid hydrocarbons and the emissions arising during the production of electricity and hydrogen (also see Chapter 4.1.4). The results for all scenarios are presented in Table 5.1.

Table 5.1: Emission factors based on the SDA of the relevant energy carriers for all four scenarios

		Emission factor in g CO_2e/kWh			
Scenario	**Energy carrier**	**2020**	**2030**	**2040**	**2050**
Trend-CoHC	Electricity	315	8	13	14
	Gas	191	168	154	116
	Liquids	253	251	0	0
	Hydrogen	252	12	19	21
Trend-Elec	Electricity	315	43	20	17
	Gas	191	190	187	138
	Liquids	253	251	248	0
	Hydrogen	252	66	29	24
Multi-CoHC	Electricity	315	8	13	14
	Gas	191	168	154	123
	Liquids	253	251	0	0
	Hydrogen	252	12	20	21
Multi-Elec	Electricity	315	44	21	17
	Gas	191	190	187	146
	Liquids	253	251	248	0
	Hydrogen	252	68	30	24

As already shown in Figure 5.9, a rapid transformation of the electricity system occurs in all scenarios. Especially in the Trend-CoHC and Multi-CoHC scenarios, the EMFs reach very low values in 2030. This is due to the fact that the strong expansion of renewable energies is the most favourable variant for offsetting the emissions generated by the transport sector. Since in the years 2040 and 2050 emissions also decrease in other domains such as the consumption sectors and other energy carriers, the pressure on the electricity supply decreases. As a result, the corresponding EMF rises slightly. The Trend-Elec and Multi-Elec scenarios show a slower but more steady decline in emissions in electricity. While the developments of the EMFs in the Elec scenarios correspond to those that were also recorded in the eXtremOS project [8], those in the CoHC scenarios are significantly more severe. The emission limit to be complied with restricts the allowance of the use of gas-fired power plants for peak load coverage in CoHC and thus requires a stronger expansion of wind and solar energy and the availability of storage capacities. To put this in concrete terms: in the years between 2020 and 2030, 44.1 GW of wind onshore, 41.3 GW of wind offshore, 33.1 GW of ground-mounted photovoltaics, and 8.3 GW of roof-mounted photovoltaics must be installed in the Elec scenarios. These already substantial efforts must be intensified in the CoHC scenarios as in these, 45.4 GW of onshore wind, 52.4 GW of offshore wind, and 62.5 GW of ground-mounted photovoltaics are installed in the same period. The expansion rate for roof-mounted photovoltaics remains the same. It becomes apparent that the expansion rates for wind onshore and roof-mounted photovoltaics are already exhausted in the Elec scenarios, while wind offshore and ground-mounted photovoltaics still represent degrees of freedom for the system. Nevertheless, the expansion figures in both scenarios are to be classified as very high and thus represent a target path rather than a realistic path.

With regard to gas, it becomes apparent that it is the only energy carrier whose EMF remains comparatively high in all scenarios. From this it can be derived that reducing emissions through the use of PtG or the import of renewable gas is more expensive for the energy system model than corresponding measures for other energy carriers such as liquid hydrocarbons. For these, EMFs are reduced to zero in the CoHC scenarios by 2040 and the Elec scenarios by 2050. This is achieved by importing renewable liquid hydrocarbons and using biogenic fuels.

The last energy carrier to be mentioned, namely hydrogen, will initially have a lower EMF than electricity in 2020. This is due to the fact that the energy carrier is still produced from gas with the help of SMR. From 2030 onwards, the supply process switches entirely to electrolysis and the EMF is thus directly related to that of electricity which is slightly increasing in all scenarios between 2020 and 2050. In this respect, the methodological comparison with the resulting costs in Table 5.2 is particularly interesting. With the exception of the Elec scenarios in 2030, hydrogen results in lower costs than electricity for all scenarios in all years. It must again be mentioned that the costs of the energy carriers are determined model-endogenously in ISAaR and thus hourly costs are taken into account. At this stage, it can be concluded that hydrogen is thus produced in those hours during which electricity costs are low. These are also the hours during which the feed-in from renewable energy sources is high and emissions in electricity are low. However, the evaluation of the EMFs is carried out on an annual basis and does not take these effects into account. Integration of the calculation of European EMFs for energy carriers into the model environment ISAaR would hence be a reasonable step. The absolute values of the costs for hydrogen increase between the years 2020 and 2030 due to the change in the provision from SMR to electrolysis using electricity. In subsequent years until 2050, the costs for hydrogen supply decrease, although the average electricity costs remain almost the same. This can be explained by the fact that the price spreads in hourly electricity costs increase and the electrolysis can subsequently be used at times when favourable electricity costs are available.

Table 5.2: Costs of the relevant energy carriers for all four scenarios

		Costs in €/MWh			
Scenario	**Energy carrier**	**2020**	**2030**	**2040**	**2050**
Trend-CoHC	Electricity	52	54	51	53
	Gas	18	31	52	42
	Liquids	39	65	111	94
	Hydrogen	28	47	40	25
Trend-Elec	Electricity	52	47	53	55
	Gas	18	32	59	45
	Liquids	39	65	103	94
	Hydrogen	28	49	35	27
Multi-CoHC	Electricity	52	54	51	54
	Gas	18	31	51	43
	Liquids	39	64	109	94
	Hydrogen	28	47	39	25
Multi-Elec	Electricity	52	47	53	55
	Gas	18	32	57	47
	Liquids	39	65	101	94
	Hydrogen	28	48	34	27

With regard to the energy carriers of gas and liquid hydrocarbons, there is initially an increase in costs until 2040. In the case of liquid hydrocarbons, this is due to the change in supply towards the import of renewable fuels. The costs of the corresponding technologies decrease towards the end of the period under consideration and thus allow for a decline in energy carrier costs between 2040 and 2050. The development of the costs for gas is similar, but with a different background. Here, costs must be incurred throughout in order to compensate for the emissions of the natural gas used until 2050 and this share increases steadily until 2050. In addition, the base costs for natural gas decline after 2040 due to lower demand, which overlays the previous effect and thus causes the costs to decrease in the last decade.

5.2.2 Sector Emissions

The resulting emissions of the transport sector are now determined from the previously derived specific emissions for energy carriers. The GHG emissions per transport carrier in all scenarios are shown in Figure 5.10.

The GHG emissions of the transport sector according to the SDA methodology amount to 175.2 Mt CO_2e in 2020. This is 10.9 Mt CO_2e more than in 2019 and 19.6 Mt CO_2e more than in 2020 as reported in the NIR [145] (also see Figure 3.5). However, the approach also includes emissions from international aviation and indirect emissions from electricity and

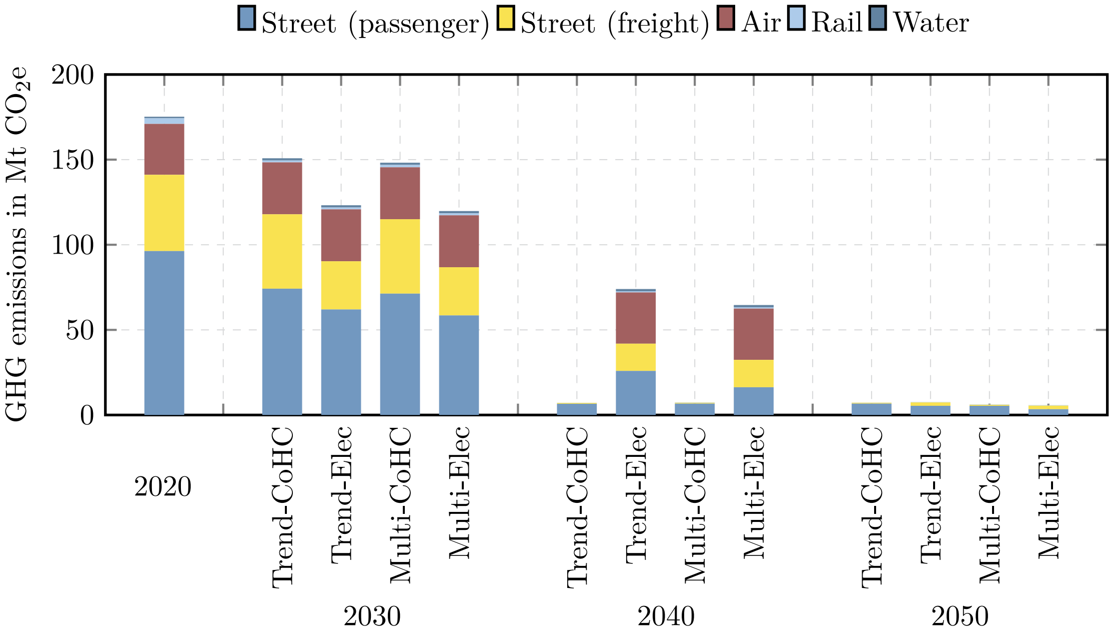


Figure 5.10: Total GHG emissions per transport carrier in the four scenarios

hydrogen production. Furthermore, in this case, the emissions of the elements of the German transport system are considered and thus, for example, the GHG emissions of foreign vehicles that refuel in Germany are not included and a direct comparison can therefore not be made at this point. The topic of the system boundaries in comparison to the NIR is further discussed in Chapter 6.1.

Split into transport carriers, 55.0 % of the GHG emissions are attributable to passenger transport by road, 25.6 % to freight transport by road, and 17.1 % to air transport. Rail transport (1.9 %) and inland vessels (0.5 %) only contribute to a very small extent to transport emissions in 2020. Although there is no direct emission cap for the transport sector over the years, the energy-system-wide cap indirectly leads to emission reductions in transport via the emission factors. Thus, GHG emissions fall to almost zero in all scenarios by 2050. In the CoHC scenarios, this even happens a decade earlier, as the EMFs from liquid hydrocarbons fall to zero due to the complete switch to renewable fuels. Given the fact that all transport sectors rely heavily on liquid hydrocarbons, total emissions also fall sharply as a result. This context is further emphasised by looking at Figure 5.11 in which the subdivision by energy carrier is shown.

In all the scenarios shown, the emissions from the use of electricity in transport are almost negligible. The increase in energy consumption, especially in the Elec scenarios, is offset by the decreasing EMF of electricity, thus keeping the corresponding total emissions low. The residual emissions in 2050 are largely due to the use of gas. As already explained in Section 4.1.4, the emissions of this energy carrier do not decrease as significantly until the end

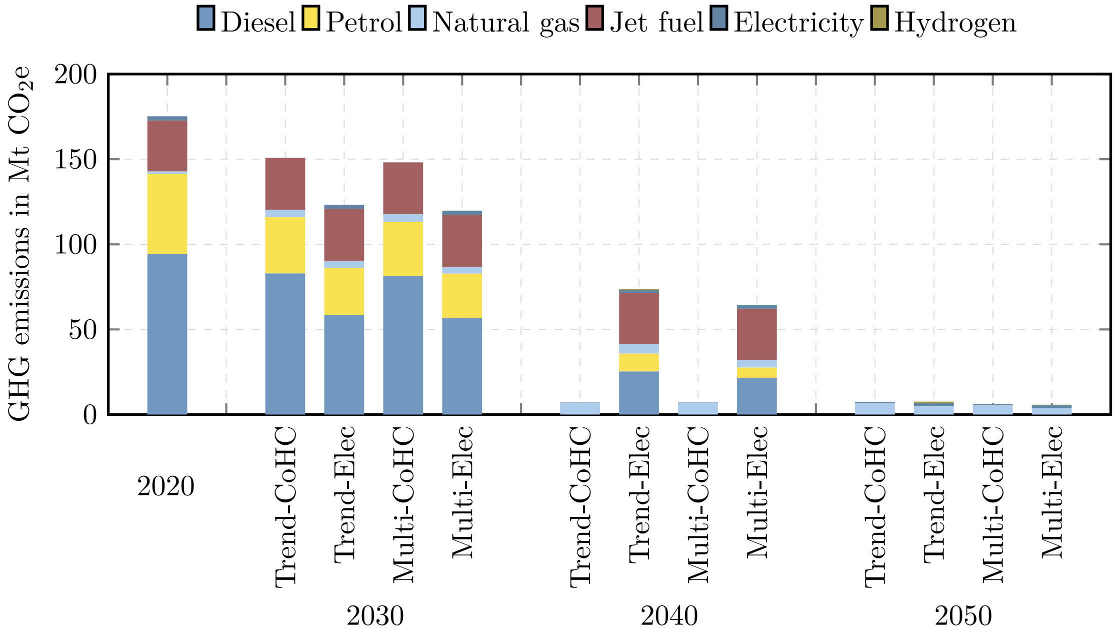


Figure 5.11: Total GHG emissions per energy carrier in the four scenarios

of the period under consideration. Thus, residual emissions from the use of gas also remain for the application sectors and, in this case, the transport sector.

To gain a deeper understanding of the origin of emissions in the scenarios, it is useful to look at the specific GHG emissions as the methodology allows for a comparison of the different vehicle types. In order to be able to do this across all transport types, the emissions are related to pkm or tkm. Figure 5.12 shows a merit order of the GHG emissions of the individual passenger vehicle types in the Trend-Elec scenario in 2030. The merit order in the y-dimension reflects the specific emissions of the individual vehicle types. In the x-dimension, the absolute emissions of the vehicle types are plotted and sorted according to their specific emissions.

In Trend-Elec, 81.1 Mt CO_2e are allocated to passenger transport in 2030 while the highest specific emissions are generated by air transport. Although the absolute emissions of domestic flights do not account for a large share of total emissions, they have the highest specific emissions at 202.8 g CO_2e/pkm. International air traffic has a larger share of the emissions shown, but due to higher load factors, it has lower specific emissions. While very high specific emissions are also associated with motorcycles, diesel and petrol cars have the largest shares of emissions. The diesel upper class vehicle has the largest share of a vehicle type due to a large number of vehicles in the fleet and comparatively high specific emissions of 105.5 g CO_2e/pkm. The plateau of specific emissions of 96.2 g CO_2e/pkm to 108.3 g CO_2e/pkm is caused by cars of the middle and upper class segments with combustion engines. Another plateau is formed by the ICEVs of the small car and compact car segments with specific emissions of 59.2 g CO_2e/pkm to 69.2 g CO_2e/pkm. In the range in between are diesel-engined local trains and line buses, which have high specific emissions due to their low capacity factors whereby those of smaller line buses and especially the coaches are lower. The latter have 14.8

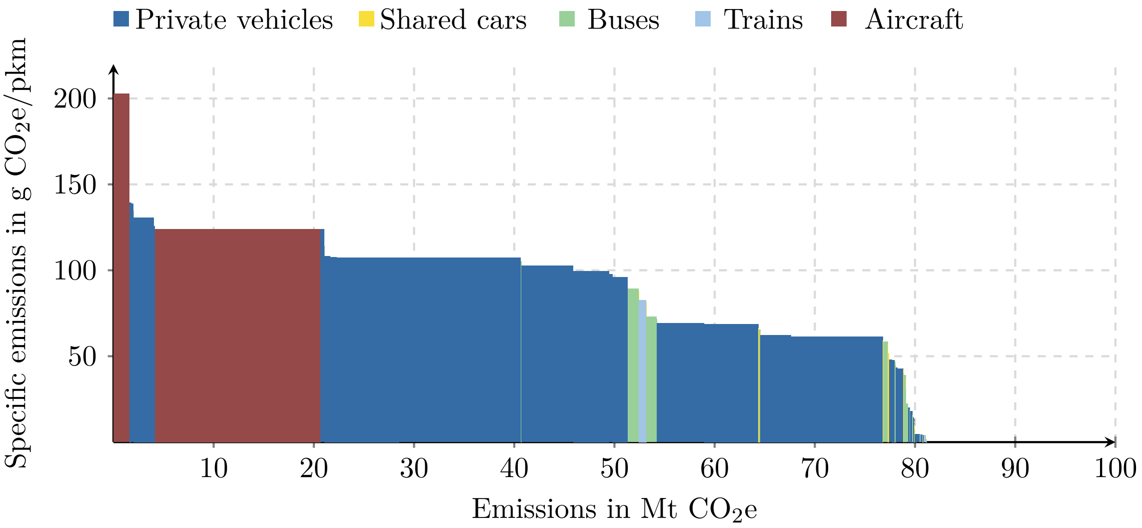


Figure 5.12: Emission merit order of vehicle types in passenger transport in the Trend-Elec scenario in 2030

respectively 22.4 g CO_2e/pkm respectively when using an ICEV. Due to the already very low emission factors of electricity in 2030, the specific emissions of electricity-powered vehicles are the lowest in the transport system in 2030. This applies to this scenario as well as all other scenarios. With the change in supply of liquid hydrocarbons in 2040 in the CoHC scenarios and in 2050 in the Elec scenarios, the specific emissions of many vehicle types drop to zero. An overview of the merit orders of all scenarios in all years for passenger transport can be found in the Appendix in Figures A.1, A.2, A.3, and A.4.

In Figure 5.13, furthermore, the merit order of emissions in freight transport can be observed for the Trend-Elec scenario in 2030. While 108 vehicle types contribute to the emissions in passenger transport in the same year of observation, there are only 17 in freight transport.

Here, too, the highest specific emissions with 1,215.8 g CO_2e/tkm are associated with air traffic and all other vehicle types have much lower values. Very large emission shares, partly as a result of the high specific emission value of 239.8 g CO_2e/tkm, are attributable to LDVs. This is understandable in comparison with the other truck technologies since the transport capacity is lower. However, when comparing the diesel MDV with the diesel HDV, the HDV performs worse due to the poor ratio of specific consumption and transport capacity. The diesel-powered semi-trailer segment has lower specific emissions of 54.7 g CO_2e/tkm. However, due to the high transport performance, the absolute emissions are high. The lowest specific emissions in diesel-powered freight transport are achieved by trains with 25.1 g CO_2e/tkm and vessels with 16.2 g CO_2e/tkm. Due to the previously mentioned low emission factor of electricity, only electricity-powered vehicle types are lower. The results for the emissions in freight transport of all scenarios can also be found in the Appendix in Figures A.5, A.6, A.7, and A.8.

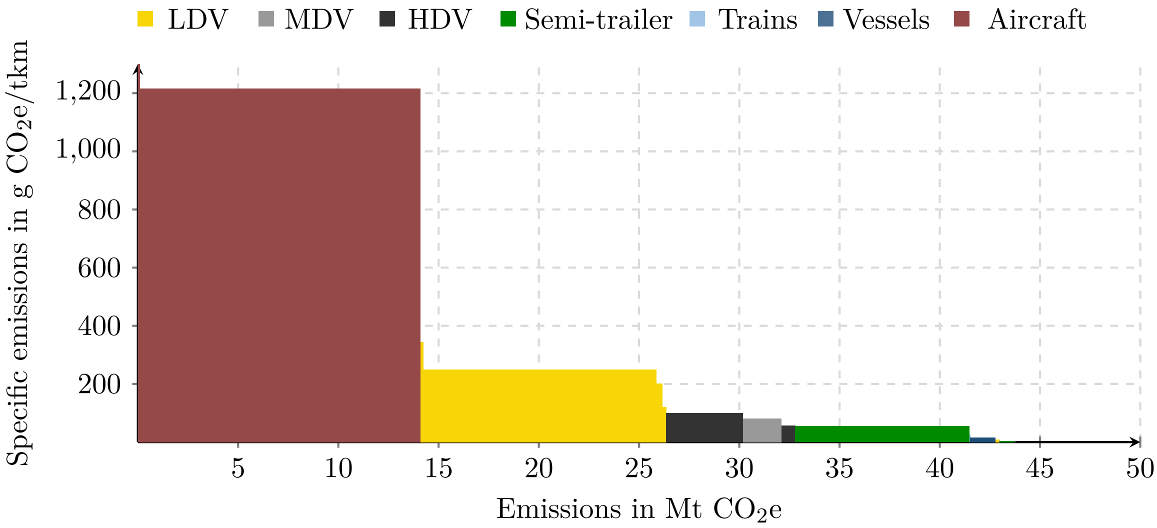


Figure 5.13: Emission merit order of vehicle types in freight transport in the Trend-Elec scenario in 2030

5.2.3 Costs

The costs of the transport sector in the present approach consist of CAPEX and fixed OPEX of the vehicles as well as energy costs. Here, the CAPEX values are annuated according to the lifetime of the vehicles. In Figure 5.14, the costs of the transport sector in the Trend-CoHC scenario are plotted by transport mode and cost type.

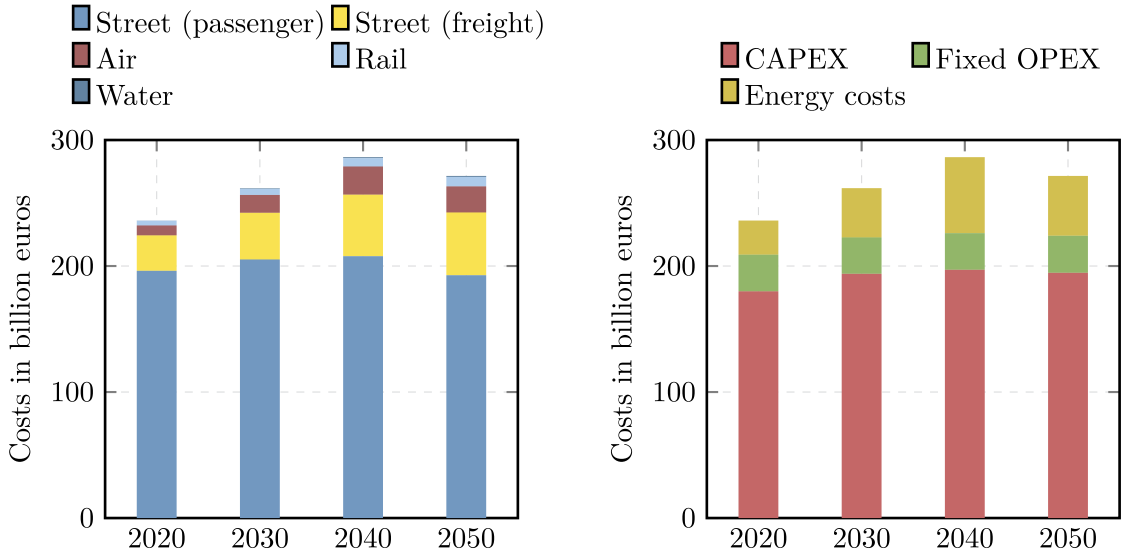


Figure 5.14: Total costs of emissions per transport carrier (left) and per cost type (right) in the Trend-CoHC scenario

The large share of road passenger transport in costs is even more evident than that shown for emissions. High vehicle costs and numbers with comparatively short lifetimes ensure that the calculated annual investment costs are very high, especially for passenger cars. In the Trend-CoHC scenario, the total costs of the sector increase until 2040, before declining slightly thereafter. The developments in passenger car transport are characterised by slightly increasing CAPEX of the conventional technologies diesel and petrol due to further efficiency measures. Towards the end of the period under consideration, it is primarily energy costs that cause costs to decline. In truck traffic, an increase in the number of vehicles and thus in costs can be observed due to the increase in transport services, especially in the LDVs segment. Here, the increase is also slowed down by the falling energy costs in the last decade (also see Table 5.2).

The Trend-CoHC scenario is now compared to the other three scenarios. For this purpose, the differential costs of the individual cost types are plotted in Figure 5.15. When comparing with the Trend-Elec scenario, it appears that the intensified electrification leads to consistently higher CAPEX. However, this is not due to the passenger cars, as a break-even of investment costs already takes place here before 2030 and they remain at a very similar level until the end of the period under consideration. Rather, the increase in investment costs in the Trend-Elec scenario is due to the use of BEV and FCEV in freight transport for which higher vehicle costs are assumed over the entire period under consideration (also see Table A.21). Nevertheless, electrification still leads to lower costs overall than the conventional scenario. The saved fixed OPEX and especially the energy costs overlay the additional costs in CAPEX in 2040 and 2050. Thus, in these years, the Trend-Elec scenario leads to annual cost savings of 16.0 billion € and 17.9 billion €, respectively. When comparing the two CoHC scenarios, the reduction in vehicle numbers due to the multimodal approach is clearly noticeable as the CAPEX are lower by 7.9 billion € in 2030, by 26.2 billion € in 2040, and by 50.6 billion € in 2050. In addition, switching to other modes of transport leads to a slight reduction in energy costs. The effects of the other two comparison scenarios overlap when looking at the Multi-Elec scenario. Although there is still a slight increase in CAPEX in 2030 compared to the scenario Trend-CoHC, the total annual costs are lower in all years. Thus, in 2040 and 2050, due to the reduction in vehicles and the reduction in energy costs, all cost components are lower than in the reference scenario. The annual relative cost savings are substantial at 20.5 % in 2040 and 21.4 % in 2050.

Analogous to the GHG emissions, a merit order for the costs is also derived to further understand the cost composition depending on the vehicle types. Figure 5.16 shows the specific costs and the total costs per vehicle type in passenger transport.

The specific highest costs would be generated by shared FCEVs with 66.5 to 136.3 €ct/pkm. However, as these do not contribute significantly to the absolute costs ($<$ 0.001 billion €), they are not visible in the graph. The costs for shared BEVs are also very high, with 34.8 to 47.7 €ct/pkm, and they are not visible in absolute values, due to an only moderate use of car sharing in the chosen scenario. The high specific costs in the transport type of car sharing vehicles is linked to the very short lifetimes of 4 years. Since these are subsequently transferred to the private fleet without a residual value consideration, they also reduce the

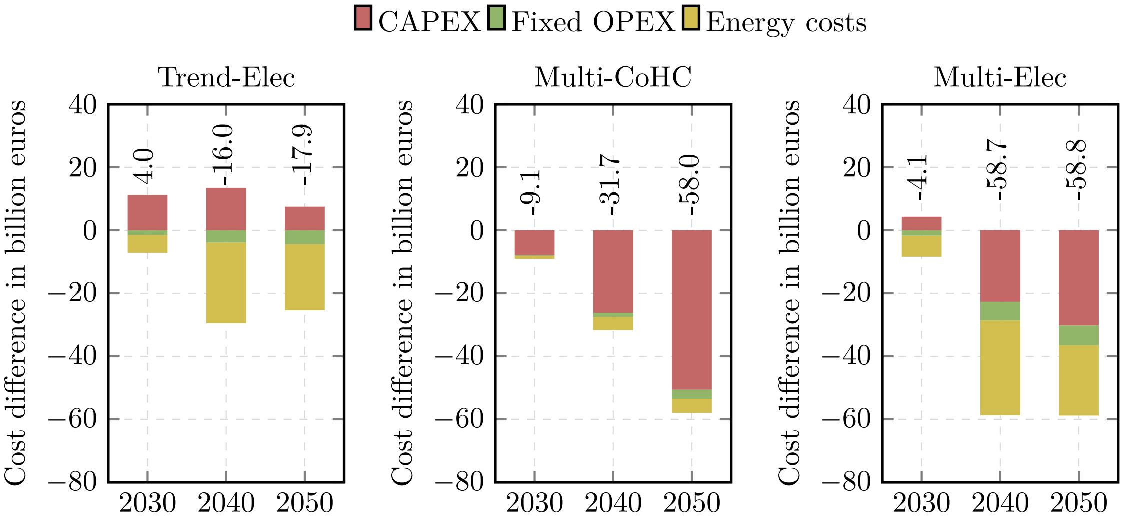


Figure 5.15: Cost comparison of the Trend-Elec (left), Multi-CoHC (middle), and Multi-Elec (right) scenarios with Trend-CoHC; positive values show an increase

costs of the private fleet. The highest specific costs that can be represented are caused by motorcycles with 63.5 €ct/pkm. Subsequently, it is especially passenger cars that are responsible for the high absolute costs but also specific costs. The specific costs of FCEVs (32.7 to 49.0 €ct/pkm) are the highest, followed by those of BEVs (17.5 to 39.8 €ct/pkm), diesel-ICEVs (15.5 to 25.4 €ct/pkm), CNG-ICEVs (15.1 to 26.5 €ct/pkm), and petrol-ICEVs (13.1 to 26.9 €ct/pkm). On comparing the BEVs with the diesel ICEVs, it can be seen that although cost parity has been achieved in one segment (medium car), the effects of the CAPEX from the previous years still have an impact on the status in 2030. Furthermore, in 2030 the costs for liquid fuels are only 38.3 % higher in relation to the energy content. This value increases to 94.3 % by 2040 in the Trend-Elec scenario (also see Table 5.2). The specific most expensive public transport is the inner city train with 18.8 €ct/pkm. The specific costs of buses range from 0.9 to 12.2 €ct/pkm, with the lower end represented by coaches and the upper end by line buses. The lowest costs are achieved by long-distance trains with 0.5 €ct/pkm and 0.8 €ct/pkm. The low costs for air transport are also striking. Here, specific costs of 7.6 €ct/pkm are incurred for national and 5.5 €ct/pkm for international transport. At this point, it should again be mentioned that infrastructure is not taken into account in this analysis (also see Chapter 4.1.6) which means, for example, that the construction of roads, railways, airports, or railway stations is neglected. Figures A.13, A.14, A.15, and A.16 in the Appendix show all cost merit orders for passenger transport.

With regard to Figure 5.17, some parallels can be drawn between specific costs and specific emissions in freight transport. The specific costs of air freight, for example, are the highest at 74.7 €ct/tkm and 55.5 €ct/tkm. They are followed by LDVs with 21.2 to 27.4 €ct/tkm, HDVs with 7.9 to 9.6 €ct/tkm, and MDVs with 4.9 to 6.6 €ct/tkm. Analogous to the costs, the clear order based on the possible transport quantity is also disrupted here by the exchange of MDVs and HDVs. This is due, in particular, to a lower quotient of specific energy consumption to

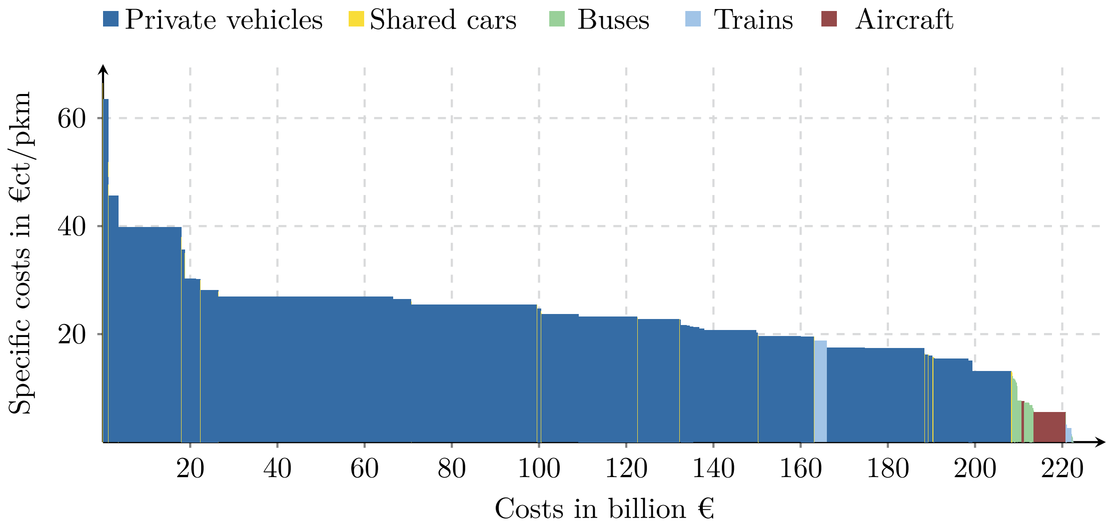


Figure 5.16: Cost merit order of vehicle types in passenger transport in the Trend-Elec scenario in 2030

transported load. However, since the data on capacity utilisation and thus the transported load is subject to great uncertainty, no conclusion can be drawn in this case. Semi-trailers represent the cheapest solution in road freight transport with 3.7 to 3.8 €ct/tkm, whereby in 2030 diesel-ICEVs are still cheaper than their electrified alternatives. The specific lowest costs in freight transport are for freight trains with 0.8 €ct/tkm and for inland waterway vessels with 0.7 €ct/tkm. Figures A.13, A.14, A.15, and A.16 in the Appendix show all cost merit orders for freight transport.

5.2.4 Preliminary Summary

In the context of this Chapter 5.2, the results of the SDA are shown and explained. The most important findings are summarised below.

Development of Total Emissions Starting from the emission factors, the specific emissions of the energy carriers were derived. It became apparent that emissions associated with electricity production will be drastically reduced in all scenarios by 2030. This means that the emissions of all technologies that use electricity will also decrease. The short-term switch to electric vehicles in the Trend-Elec and Multi-Elec scenarios thus leads to a reduction from 150.8 Mt CO_2e to 120.9 Mt CO_2e and from 148.2 Mt CO_2e to 119.8 Mt CO_2e, respectively, in 2030. In 2040, the situation changes, as the Trend-CoHC and Multi-CoHC scenarios result in a shift in the overall supply of liquid hydrocarbons away from fossil fuels toward renewable fuels. With a view to achieving climate protection targets, the safer option is therefore to further expand both options. For the short-term reduction of GHG emissions in transport, electrification is the most suitable solution and further progressive conversion of electricity generation towards larger shares of renewable energies is a prerequisite here. However, to

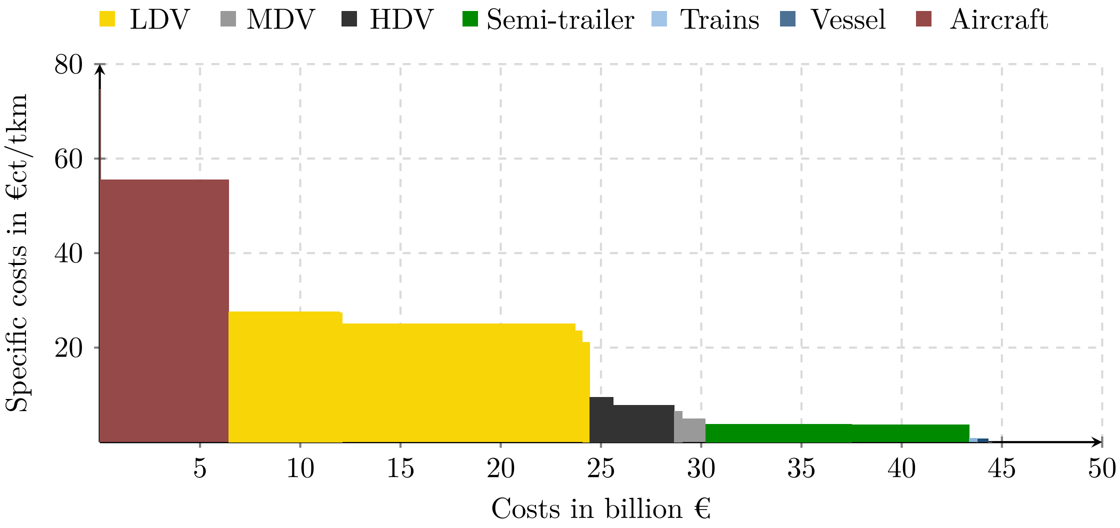


Figure 5.17: Cost merit order of vehicle types in freight transport in the Trend-Elec scenario in 2030

ensure that the remaining vehicle fleets that will not be electrified can also reduce their emissions, renewable fuels must be available in the medium term. This is also essential for air and shipping traffic in order to reduce emissions.

Development of Total Costs The consideration of costs also provides results in the comparison of the scenarios. In general, greater electrification leads to higher CAPEX. However, in almost all cases, these are more than compensated by the reduction in fixed OPEX and energy costs. Especially the energy costs for electricity are lower in the medium and long term than those for liquid fuels. This is due to the fact that, in the future, renewable electricity can be provided more cheaply than renewable fuels or fossil fuels with CO_2 compensation. Furthermore, the analyses show a significant reduction in CAPEX through an increase in multimodality with a simultaneous reduction in passenger cars. Since the investment costs of passenger cars in particular account for the largest share of transport sector costs, the leverage at this point is high. This is also shown by the analysis of specific costs. Although the specific costs for car sharing are very high, they represent enablers for multimodality and thereby the increased use of public transport. These in turn have very low specific costs.

Methodological Limitations Methodological limitations must also be highlighted when deriving the statements. With regard to the emission factors and the specific costs of energy carriers, the values for hydrogen are particularly striking. In terms of emissions, annual balance calculations are drawn up. Thus, according to the explanations in Chapter 4.1.4, the annual emission factor of hydrogen is directly related to that of electricity. In contrast, the costs are calculated hourly within the model ISAaR. The economic optimisation model determines that the use of the electrolysers takes place during the hours when cheap electricity is available. This leads to the fact that the costs for hydrogen in relation to the energy content are lower than those for electricity in almost all cases. However, the fact that the shares of renewable energies are higher in these hours than during the expensive hours leads to the conclusion that the emission factors of hydrogen are estimated to be too high. This applies to all domestic Power-to-X (PtX) conversions. Since the shares of PtG and PtL in the supply of gas and liquid fuels is very small and the absolute demand for hydrogen in the scenarios is very low, the resulting error can be considered small. Nevertheless, an integration of the emission factor calculation into the ISAaR model must be performed to remedy these methodological limitations.

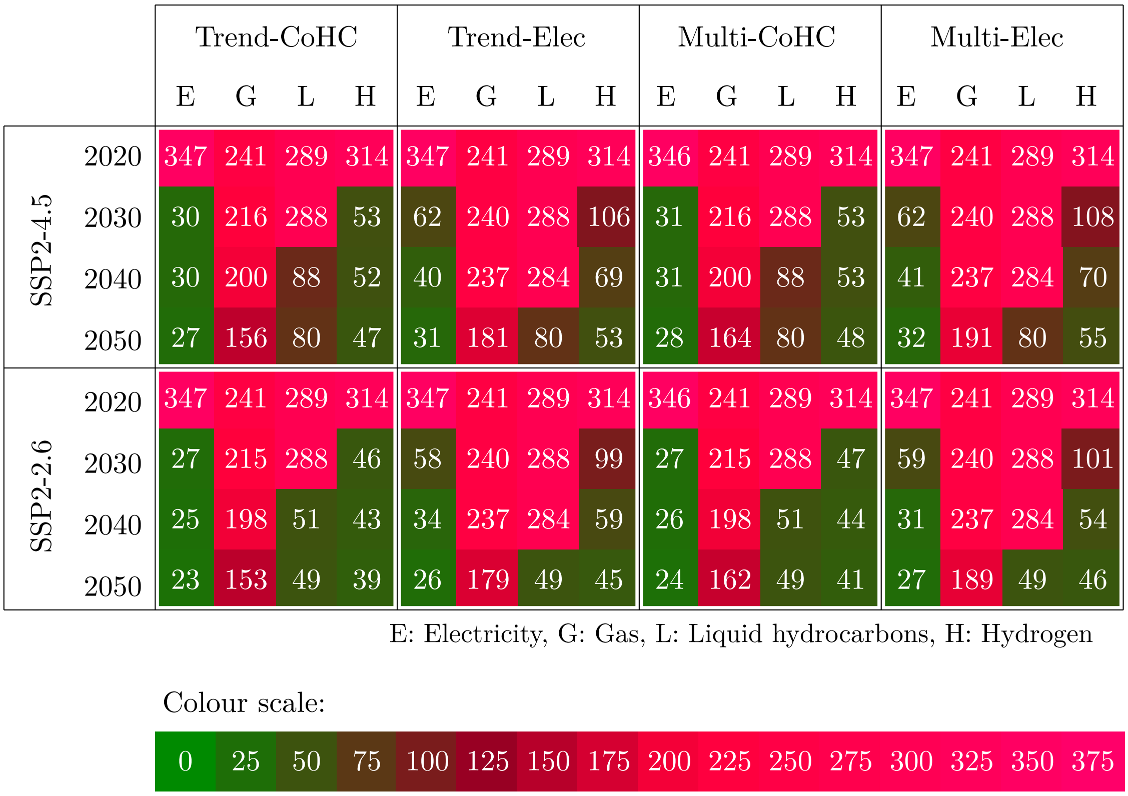
5.3 System-Dynamic Life Cycle Assessment

In the following, the results of the SDLCA are discussed. First, the emission factors of the energy sources used in transport are examined in Chapter 5.3.1 and the differences in emissions compared to the SDA are shown. In Chapter 5.3.2, the emissions are supplemented by the non-operational emissions before Chapter 5.3.3 deals with their origins in the course of a contribution analysis. Finally, in Chapter 5.3.4 the relevance of the location of battery production is examined in the course of a sensitivity analysis.

5.3.1 Expanded Emission Factors and Operational Emissions

In order to be able to determine the GHG emissions in operation, EMFs are derived first. In addition to the direct emissions of the energy carriers, the EMFs also include the construction of energy conversion technologies and the primary energy supply, e.g. fossil oil or gas. Figure 5.18 shows the emission factors in all scenarios of all eight combinations of transport and European energy scenarios with global background scenarios.

As was to be expected, the EMFs derived from SDLCA are always higher compared to the EMFs from the SDA in Table 5.1 due to the inclusion of upstream emissions. Looking at 2020, the EMF of electricity is 10.2 %, that of gas 26.2 %, that of liquid hydrocarbons 14.2 %, and that of hydrogen 24.6 % higher than the values in the SDA evaluations. The largest increase was recorded for gas. This is largely due to emissions from the supply of fossil natural gas, which are based on methane leakage during transport and extraction. Another smaller part of the increase is due to the biogas share of 5.1 %, which in the course of the SDLCA is no longer accounted for with 0 g CO_2e/kWh but with 58.5 g CO_2e/kWh. Since the supply of hydrogen in 2020 is exclusively derived from steam reforming, the increase of the EMF is similar to that of gas. The increase in emissions due to the integration of the upstream chain in liquid hydrocarbons and electricity is significantly lower at 14.2 % and 10.2 %, respectively. However, a significant increase in the relevance of the upstream chain can be seen in the development over the next few years. With the increase in the share of renewable energies in



		Trend-CoHC				Trend-Elec				Multi-CoHC				Multi-Elec			
		E	G	L	H	E	G	L	H	E	G	L	H	E	G	L	H
SSP2-4.5	2020	347	241	289	314	347	241	289	314	346	241	289	314	347	241	289	314
	2030	30	216	288	53	62	240	288	106	31	216	288	53	62	240	288	108
	2040	30	200	88	52	40	237	284	69	31	200	88	53	41	237	284	70
	2050	27	156	80	47	31	181	80	53	28	164	80	48	32	191	80	55
SSP2-2.6	2020	347	241	289	314	347	241	289	314	346	241	289	314	347	241	289	314
	2030	27	215	288	46	58	240	288	99	27	215	288	47	59	240	288	101
	2040	25	198	51	43	34	237	284	59	26	198	51	44	31	237	284	54
	2050	23	153	49	39	26	179	49	45	24	162	49	41	27	189	49	46

E: Electricity, G: Gas, L: Liquid hydrocarbons, H: Hydrogen

Colour scale:

0	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375

Figure 5.18: Emission factors based on the SDLCA of the relevant energy carriers for all four transport scenarios and both global background scenarios

the provision of all energy carriers, the relevance of the upstream chain in the EMF increases. With regard to electricity, the EMF in the Trend-Elec scenario falls from 347 g CO_2e/kWh to 62 g CO_2e/kWh in 2030 in the SDLCA and is thus 44.2 % higher than that in the evaluation of the SDA. This increase is even more pronounced in the CoHC scenarios, which already show very high shares of renewable energy in 2030. This effect is apparent for all energy carriers. As a large share of fossil natural gas is still used in all scenarios in 2050 (also see Figure 5.9), the EMF does not decrease as much and the increase due to the integration of the upstream chain is not as significant as for the other three energy carriers.

The development of the EMFs of the SDLCA over the years clearly shows the change in energy supply in all energy carriers. In the electricity sector, as already mentioned, this change already becomes apparent in the years between 2020 and 2030. Here, the continuing transition from thermal power plants to renewable energies ensures that emissions fall sharply. This development continues in the Elec scenarios after 2030 until an EMF of 26 to 32 g CO_2e/kWh is reached in 2050. In the CoHC scenarios, such low EMFs of 27 to 31 g CO_2e/kWh are already reached in 2030. In the case of hydrogen, the switch from gas to electricity takes place entirely in the years up to 2030 in all scenarios. Subsequently, the EMF of hydrogen decreases accordingly to the EMF of electricity. The conversion of the main share of liquid hydrocarbon supply from fossil oil to the import of synthetic fuels takes place in the CoHC scenarios from 2030 to 2040 and in the Elec scenarios from 2040 to 2050. In all scenarios, the EMF for liquid hydrocarbons is reduced by 72.3 % to 80 g CO_2e/kWh and by 83.0 % to 49 g CO_2e/kWh, respectively. Since there is no complete change in the supply of gas away from fossil natural gas, the reduction in EMF is correspondingly moderate compared to the other energy carriers.

If the two background scenarios are now compared, a faster reduction of the EMFs is observed in the scenarios SSP2-2.6. These differences can vary in magnitude. For example, the EMFs of electricity in the SSP2-4.5 scenarios are 16.7 % to 19.2 % higher than those of the SSP2-2.6 scenario. On the contrary, for liquid hydrocarbons, the difference is much larger at 63.3 %. This is due to the fact that the imported fuels in 2050 are based purely on photovoltaics. The production of photovoltaic modules, in turn, is energy-intensive and strongly dependent on global emission factors for electricity. These differ significantly in the two scenarios. The German electricity system and thus also the EMF for electricity are based to a large extent on wind energy. The higher full load hours of wind in Germany compared to photovoltaics in Morocco ensures a lower EMF of electricity, which is reflected accordingly in the emissions of the energy carriers of electricity and liquid fuels.

When looking at transport scenarios and the resulting energy demands, the individual effects of the EMFs overlap. Figure 5.19 shows the GHG emissions caused by the energy demand in the operational phases of the four transport scenarios. In addition, the increase is shown in comparison to the evaluations of the SDA. In each case, the background scenario SSP2-4.5 was used in the illustrations.

The developments of the GHG emissions of the four scenarios are similar to those from the SDA. Only when reaching the year 2040 in the CoHC scenarios and 2050 in the Elec scenarios does a clear difference become apparent. Before that, the increase due to the integration of the upstream chain of energy carriers is 14.3 % to 15.3 %. This is mainly due to the fact that the transport sector is characterised by the high consumption of liquid hydrocarbons and thus the value of the increase is similar to that of liquid hydrocarbons. With the change in the supply of this energy carrier in 2040 in the CoHC scenarios, the increase due to the integration of upstream chain emissions rises to 657.2 % and 592.8 %, respectively. This large increase can be explained by the fact that the liquid hydrocarbons provided with synthetic fuels have an EMF of 90.0 g CO2e/kWh in the SDLCA instead of 0 g CO2e/kWh in the SDA. The weighted average value with biofuels in 2040 in both CoHC scenarios then results in 87.8 g CO2e/kWh (also see Figure 5.18).

Furthermore, the value in the Trend-CoHC scenario is higher than that of the Multi-CoHC scenario. In particular, this is due to the fact that the change to car sharing also implicitly leads to increased changes in the energy carrier used for electricity since there are more electrified cars in the shared fleet. The small changes in energy demand provide a noticeable change in the relative increase in GHG emissions. A significant increase due to the integration of upstream chain emissions in the Elec scenarios results in 2050. This was also already shown

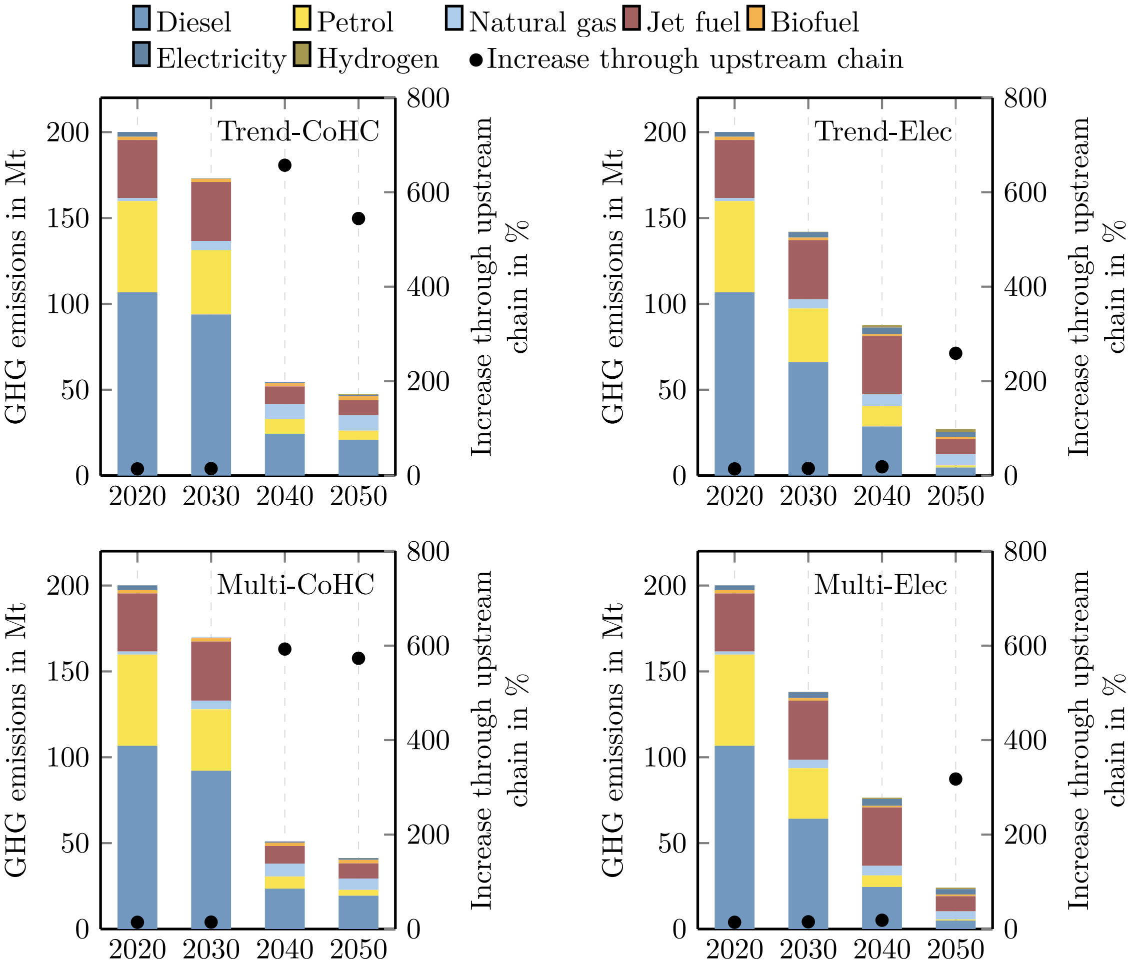


Figure 5.19: Development of GHG emissions caused by energy demand in the operating phase of the scenarios Trend-CoHC (top left), Trend-Elec (top right), Multi-CoHC (bottom left), and Multi-Elec (bottom right), evaluated through SDLCA with the SSP2-4.5 as a background scenario; the increase through the inclusion of the GHG emissions arises from the provision of primary energy carriers and the production of energy conversion technologies

in Pichlmaier et al. [133]. The increase amounts to between 259.0 % and 317.6 % and is thus significantly lower than that in the CoHC scenarios. Nevertheless, the GHG emissions are thus significantly higher than those in the evaluations in the course of the SDA.

Subsequently, the GHG emissions from the production of the end-of-life phases of the vehicles are now added to the energy-related operating emissions.

5.3.2 Sector Emissions

In addition to the GHG emissions caused by the use of energy in the operating phase, those from the production and end-of-life phases of the vehicles are now discussed. The resulting total emissions for all scenarios are displayed in Figure 5.20.

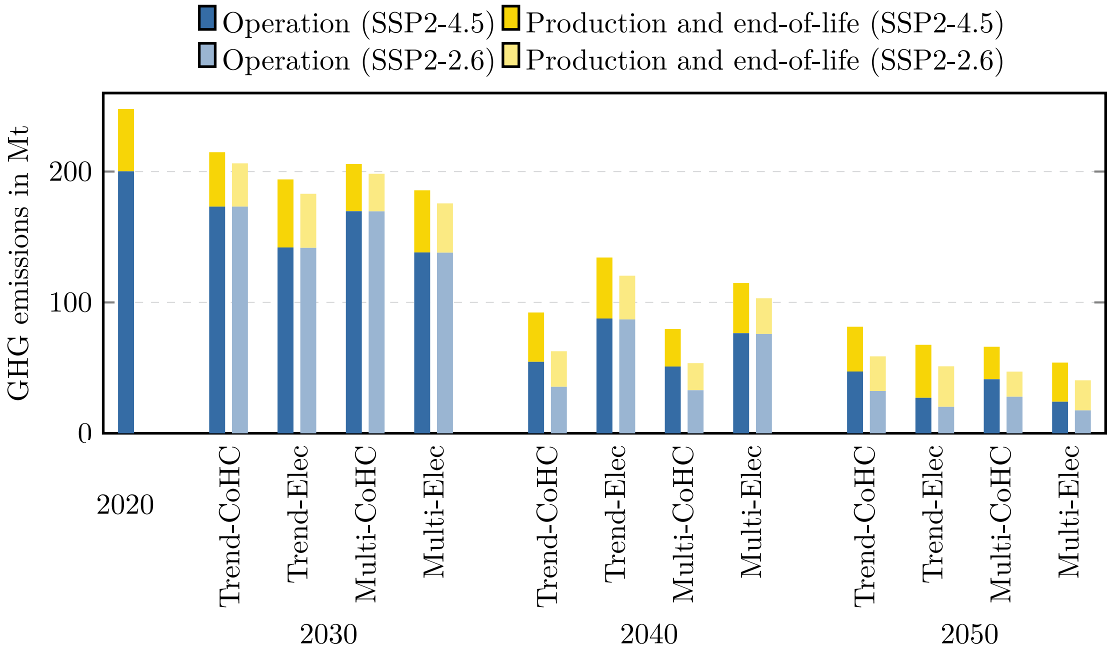


Figure 5.20: Total GHG emissions per transport carrier in the four scenarios

The plot indicates that with the exception of the Elec scenarios in 2050, the operational emissions account for the larger part of emissions in all scenarios and years. In 2020, the GHG emissions caused by production and end-of-life amount to 47.6 Mt CO_2e. This corresponds to 19.2 % of the total emissions (also see Table 5.3). Using the background scenario SSP2-4.5, emissions in the Trend-CoHC and Trend-Elec scenarios decrease to 34.2 Mt CO_2e and 40.5 Mt CO_2e, respectively, by 2050. This corresponds to shares of 42.1 % and 59.9 % of total emissions in these years. The higher emissions in the electrification scenario are due to the higher production expenditure of electrified vehicles (also see Chapter 5.3.3). Significantly lower production and end-of-life emissions result in the Multi-CoHC and Multi-Elec scenarios. The strong decrease in passenger cars reduces the emissions to 24.8 Mt CO_2e and 29.9 Mt CO_2e in 2050. All values for the GHG emissions from production and end-of-life for the background scenario SSP2-4.5 are presented in Table 5.3.

From this, it is apparent that the shares of GHG emissions caused by production and end-of-life mostly increase in their share of total emissions which suggests that the provision of energy for operation is subject to more rapid change than the background processes related to vehicle production. The only exception to the steady increase in the share is the Multi-CoHC scenario, which shows a decrease between 2020 and 2030. This is due to the strongly decreasing vehicle numbers with moderately decreasing operating emissions in this period.

Looking at the more progressive background scenario SSP2-2.6, it is obvious that absolute emissions further decrease. In 2050, 26.5 Mt CO_2e and 31.0 Mt CO_2e are achieved by the

Table 5.3: GHG emissions arising from the production and end-of-life of vehicles in absolute values and relative to the total emissions in the corresponding year; background scenario SSP2-4.5

	Year	**Trend-CoHC**	**Trend-Elec**	**Multi-CoHC**	**Multi-Elec**
Absolute in Mt CO_2e	2020	47.6	47.6	47.6	47.6
	2030	41.6	52.0	36.1	47.5
	2040	37.7	46.6	28.7	38.3
	2050	34.2	40.5	24.8	29.9
Relative in % of total emissions	2020	19.2	19.2	19.2	19.2
	2030	19.4	26.8	17.6	25.6
	2040	40.9	34.7	36.0	33.3
	2050	42.1	59.9	37.5	55.4

Table 5.4: GHG emissions arising from the production and end-of-life of vehicles in absolute values and relative to the total emissions in the corresponding year; background scenario SSP2-2.6

	Year	**Trend-CoHC**	**Trend-Elec**	**Multi-CoHC**	**Multi-Elec**
Absolute in Mt CO_2e	2020	47.6	47.6	47.6	47.6
	2030	33.1	41.3	28.7	37.7
	2040	27.2	33.4	20.7	27.3
	2050	26.5	31.0	19.2	23.0
Relative in % of total emissions	2020	19.2	19.2	19.2	19.2
	2030	16	22.5	14.5	21.5
	2040	43.4	27.7	38.6	26.5
	2050	45.1	60.6	40.8	56.8

Trend-CoHC and Trend-Elec scenarios, and 19.2 Mt CO_2e and 23.0 Mt CO_2e by the Multi-CoHC and Multi-Elec scenarios. The results are listed in Table 5.4.

At this point, particular attention should be paid to the differences between the CoHC and Elec scenarios in the changes in relative share from SSP2-4.5 to SSP2-2.6 as the changes in the CoHC scenarios are always higher. As an example, the year 2050 can be considered. In the Trend-CoHC scenario, the share of emissions from production and end-of-life is 42.1 % in the background scenario SSP2-4.5 and 45.1 % in the background scenario SSP2-2.6. The differences are smaller in the Trend-Elec scenario which is again due to the high relevance of the background scenario for the production of synthetic fuels (also see Figure 5.18).

5.3.3 Contribution Analyses of Non-Operational Emissions

In order to learn more about the method, its possibilities and limitations, the non-operational emissions will now be examined more closely. For this purpose, the GHG emissions of the entire fleet are first broken down into their transport types (Figure 5.21).

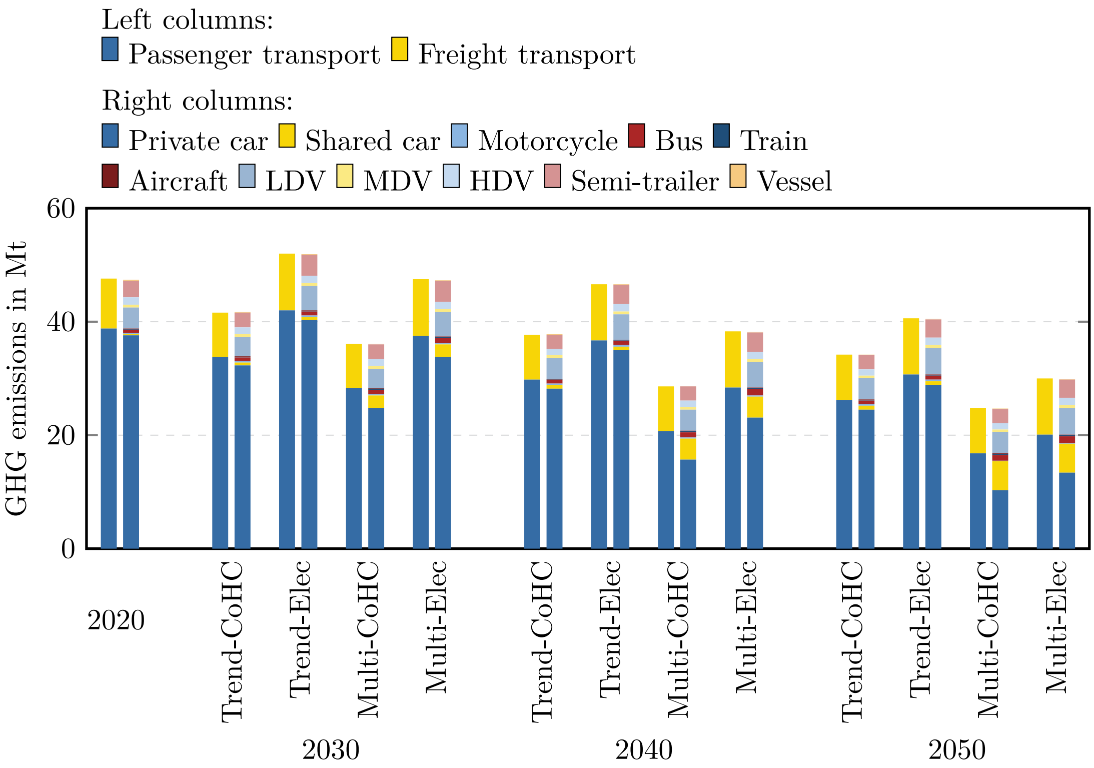


Figure 5.21: Non-operational GHG emissions of vehicles in the four scenarios; background scenario SSP2-4.5

In 2020, the share of GHG emissions caused by production and end-of-life for passenger transport is 81.5 %. This share decreases steadily in all scenarios, as the number of cars decreases while freight transport and especially delivery transport increases, and thus the number of LDVs also increases. Nevertheless, the share of passenger transport remains larger than that of freight transport in all scenarios and years. It becomes clear that the share of GHG emissions associated with privately used cars is the largest. Due to the strongly decreasing number of passenger cars in the Multi scenarios, this share decreases in these scenarios. The increasing share of shared vehicles does not compensate for this decrease. Other significant contributions are associated with LDVs and semi-trailers. Trains, ships, and aircraft, in particular, have a small share in the annual emissions due to their small absolute number and their long lifetimes.

In order to better understand the differences in the various scenarios, the individual vehicle types and hence the technologies of the private car transport types are now considered. Unlike before, these are not seen in the context of the entire fleet, but rather specifically regarding the emissions associated with the production and end-of-life of the individual vehicles. The corresponding emissions for diesel-ICEVs, BEVs, and FCEVs are plotted in Figure 5.22.

The lowest GHG emissions in the start year as well as in all subsequent years in both background scenarios are to be found in the ICEVs. These have 9.0 to 13.0 t CO_2e in 2020 and 6.3

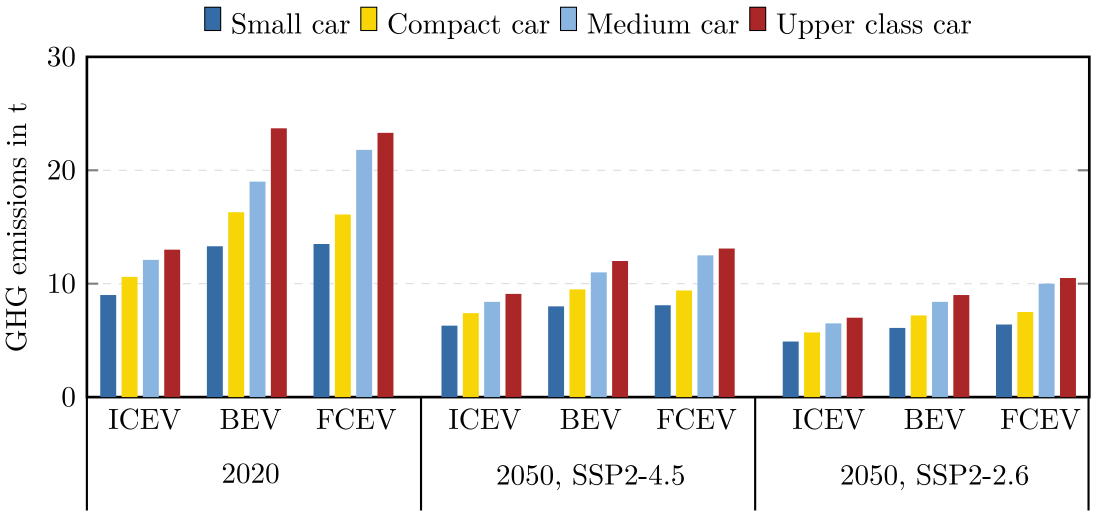


Figure 5.22: GHG emissions for production and end-of-life of cars; ICEV are represented by diesel-powered cars

to 9.1 t CO_2e in 2050 in the scenario SSP2-4.5 and 4.9 to 7.0 t CO_2e in the scenario SSP2-2.6, respectively. Especially in 2020, the values of the other two propulsion technologies are much higher. Thus, BEVs have 13.3 to 23.7 t CO_2e and FCEVs 13.5 to 23.3 t CO_2e. It is noticeable that the GHG emissions associated with the BEVs in the medium class are lower than those of the FCEVs. The decisive factor for the design of energy storage and drivetrain in FCEVs is the necessary power. This leads to higher emissions in the medium class and is reversed for the upper class vehicles. The relevant dimensioning criterion at this point is the range to be achieved. Because of a very high necessary range, the battery capacity of the BEVs in this category (112 kWh) is much higher than that of the medium class (52 kWh). By 2050, the emissions of the alternative drive technologies BEV and FCEV decrease strongly in both scenarios. In 2050, the emissions of BEVs are consistently lower than those of FCEVs. To understand this further, Figure 5.23 breaks down the emissions of small and upper class cars into their components.

For the ICEVs in 2020 and in 2050 for both scenarios, the largest emission shares are attributable to the production of the glider. In 2020, the corresponding share is 69.8 to 73.2 % for small cars and 73.7 to 75.7 % for upper class cars. The shares do not increase significantly until 2050. Other notable contributions to the non-operational emissions are only made by the powertrain. The production of the tank and the end-of-life lead to almost no emissions. The latter fact is also recognisable for all other technologies. This is due to the cut-off approach (also see Chapter 4.2.4), in which only non-recycled materials contribute to this life cycle phase. In the case of vehicles, the corresponding share is so small that the absolute amounts of emissions that are assigned to this phase reach a maximum of 0.013 t CO_2e and are thus negligible. In the technologies HEV, PHEV, BEV, and FCEV, the glider also leads to significant shares of the emissions, but here the shares of the energy storage are also relevant. The GHG emissions for the energy storage of BEVs in 2020 are 3.8 t CO_2e in small cars and

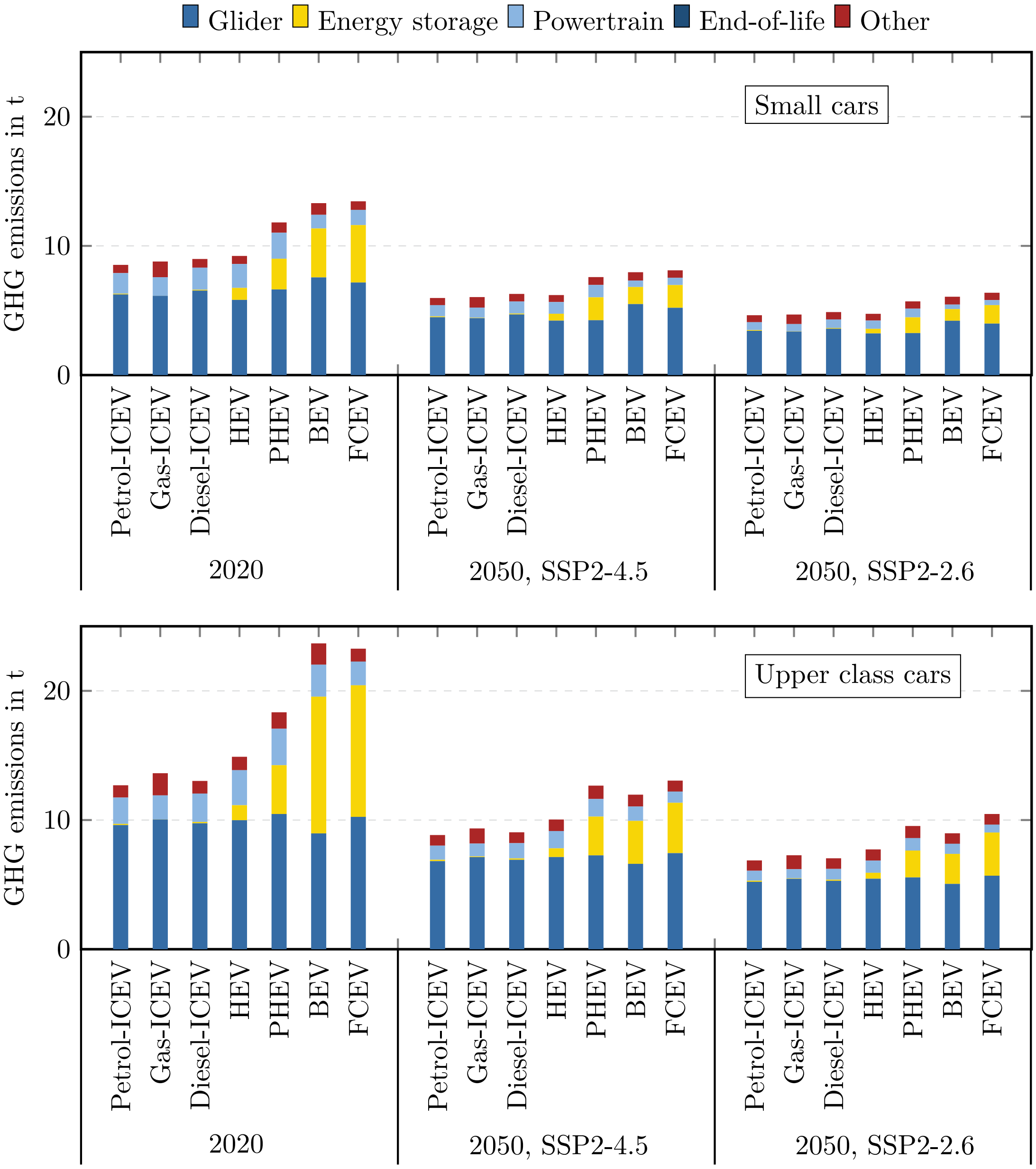


Figure 5.23: Contribution analysis of GHG emissions associated with the production and end-of-life of small cars (top) and upper class cars (bottom)

10.6 t CO_2e in upper class vehicles. In particular, the production of battery cells and their electricity demand are decisive in this case. For FCEVs, they are similarly high and account to 4.5 t CO_2e and 10.2 t CO_2e. The production of the materials for the tanks and the fuel cell, which is a part of energy storage here, are the most extensive.

In the course of the development over the period under consideration, the GHG emissions for the production of the energy storages decrease more than those of the gliders. This can be seen in the case of battery storage in particular. This highlights a challenge of the life cycle assessment at this point. In the present analysis, on the one hand, electricity has shifted large proportions of the deployment technologies to other processes as the background scenarios have been adjusted. Thus, large amounts of photovoltaic and wind energy are used. On the other hand, in the area of steel production, which is essential for the production of the glider, no adjustment of the background data takes place. Thus, there are no process route changes here, such as the change to direct iron reduction with hydrogen. This topic is already addressed in the life cycle assessment standard DIN EN 14040/14044 by iteratively defining the method. Accordingly, a further step at this point would include the adjustment of the input data.

Another noticeable aspect is the fact that the glider of the PHEV in the upper class car causes the GHG emissions to be higher than those of the BEV. This is due to the data basis used and the underlying assumptions. The total weight of the respective vehicles is derived from the current structure of purchased vehicles of the respective technologies. In the case of PHEVs, these are very heavy vehicles that have mostly been modified from conventional ICEVs. On the contrary, current BEVs are often purpose-built vehicle models where a great deal of emphasis is put on weight saving. However, other vehicle types could also experience this development in the future. Accordingly, the different values for the respective gliders are subject to strong uncertainties.

Additional uncertainties concern the battery production and its future location which will be discussed in the following chapter.

5.3.4 Sensitivity Case: The Relevance of the Location of Battery Production

The production of battery cells, especially for long-term scenarios, represents an uncertainty in all analyses. As of 2017, 49 % of battery cells were manufactured in China. Other notable locations of battery production are the US with 20 %, Europe with 12 %, South Korea with 5 %, and Japan with 3 % [7]. To create a stronger position in this area, the Important Projects of Common European Interest (IPCEI) initiative was launched in 2019 by the EU, which aims to further advance the extraction of raw materials, production of cells and modules, and system, repurposing and recycling, and refining in Europe [146]. This has had an impact in that projects have been announced to increase annual production battery cell production capacity by more than 1,110 GWh by 2030 [147]. More than half of these are already expected to be built by 2025. To classify this, the electrification scenario Trend-Elec is used. In this scenario, 1.7 million BEVs will be registered in Germany in 2030 with battery capacities between 32.4 kWh and 112.0 kWh. In total, this results in a necessary battery capacity of 101 GWh during this year. Although this figure does not include the necessary battery capacities of other countries and other transport areas as well as imports and exports, it is assumed that the supply chain structure will change significantly.

Due to the high level of uncertainty regarding the future locations of battery production for vehicles in Germany, this is now varied in the following. In the reference case, and thus for the previous evaluations, a global distribution of production was assumed and therefore a global energy mix was used. In the sensitivity analysis, this production is now to be relocated once completely to China and once completely to Europe. First, the effects on the emissions in the battery production are taken into consideration. Figure 5.24 shows these emissions for the various locations. The values are shown per kWh battery capacity (kWh_{cap}) in the illustration and in the following descriptions.

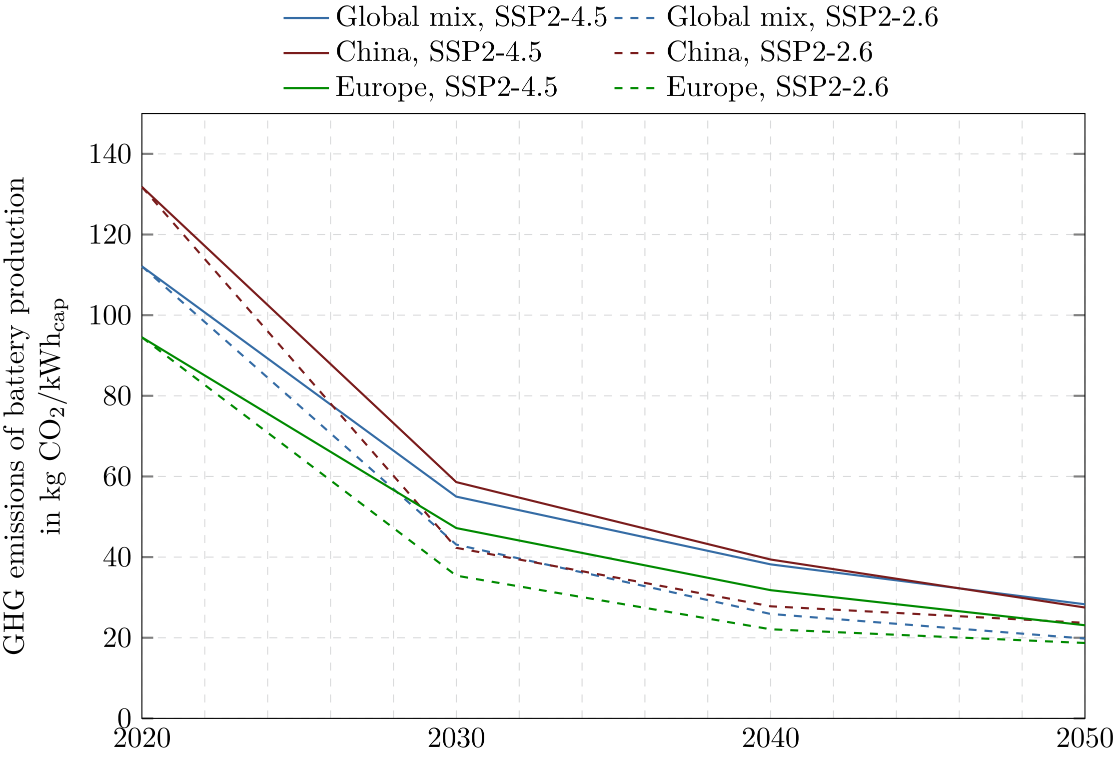


Figure 5.24: GHG emissions of battery production

The electricity demand for battery production is only varied over time and is the same across all scenarios and locations. It decreases from 57.3 kWh/kWh_{cap} in 2020 to 28.5 kWh/kWh_{cap} in 2030, 22.6 kWh/kWh_{cap} in 2040, and 18.1 kWh/kWh_{cap} in 2050. However, with a view to 2020, the GHG emissions in battery production differ significantly between the various locations. In the reference case global mix, the GHG emissions of battery production in 2020 are 112.1 kg CO_2/kWh_{cap}. If the location is changed to China, the emission factor increases to 131.8 kg CO_2/kWh_{cap}, and if the location is changed to Europe, it decreases to 94.5 kg CO_2/kWh_{cap}. This is due to the different emission factors of electricity of 0.77 kg/kWh in China, 0.55 kg/kWh in the global mix, and 0.35 kg/kWh in Europe.

This initial difference based on location is overlaid in the course of the scenarios by the effects resulting from the scenarios SSP2-4.5 and SSP2-2.6. The scenario SSP2-4.5 shows a comparatively small medium-term decrease in the emission factor for electricity in China and only by 2050 will China's emission factor be lower than that of the global mix. The situation is different in scenario SSP2-2.6, in which China drastically reduces its emissions in electricity production by 2030. The emissions are subsequently higher than those of the global mix, but at a generally very low level of less than 0.10 kg/kWh. The evaluation very clearly shows the relevance of China's short-term emission reduction to achieve the goal of limiting the increase in global average temperature to well below 2 °C. However, in both scenarios, battery production emissions decrease significantly from 131.8 kg CO_2/kWh_{cap} to 90.1 kg CO_2/kWh_{cap} in 2030, 78.3 kg CO_2/kWh_{cap} in 2040, and 71.9 kg CO_2/kWh_{cap} in 2050, and 75.1 kg CO_2/kWh_{cap} in 2030, 66.6 kg CO_2/kWh_{cap} in 2040 and 65.1 kg CO_2/kWh_{cap} in 2050, respectively.

Regarding the shift of battery production to Europe, emissions from electricity generation are significantly lower than in China and the global mix. Emission factors of 0.21 kg/kWh in 2030, 0.13 kg/kWh in 2040, and 0.07 kg/kWh for electricity are achieved in the SSP2-4.5 scenario. This results in battery production emissions of 47.2 kg CO_2/kWh_{cap} in 2030, 31.8 kg CO_2/kWh_{cap} in 2040, and 23.1 kg CO_2/kWh_{cap} in 2050. Emissions in the SSP2-2.6 scenario are even lower. Due to the emission factors of electricity of 0.08 kg/kWh in 2030, 0.03 kg/kWh in 2040, and 0.02 kg/kWh in 2050, the emissions of battery production are 35.4 kg CO_2/kWh_{cap} in 2030, 22.1 kg CO_2/kWh_{cap} in 2040, and 18.7 kg CO_2/kWh_{cap} in 2050.

The relative deviations of production in China and in Europe from the reference case are shown in Table 5.5 which indicates that battery production is highly dependent on the location and the prevailing emission factors.

Table 5.5: Relative deviations in emissions in battery production from the reference case of using the global mix for battery production

	China		**Europe**	
Year	**SSP2-4.5**	**SSP2-2.6**	**SSP2-4.5**	**SSP2-2.6**
2020	17.5 %	17.5 %	-15.7 %	-15.7 %
2030	6.4 %	-1.8 %	-14.2 %	-17.8 %
2040	3.2 %	7.5 %	-16.8 %	-14.5 %
2050	-2.8 %	19.9 %	-18.4 %	-5.4 %

Finally, in order to determine whether the change in the location of battery production causes significant changes in the non-operational emissions of the entire transport sector, the derived

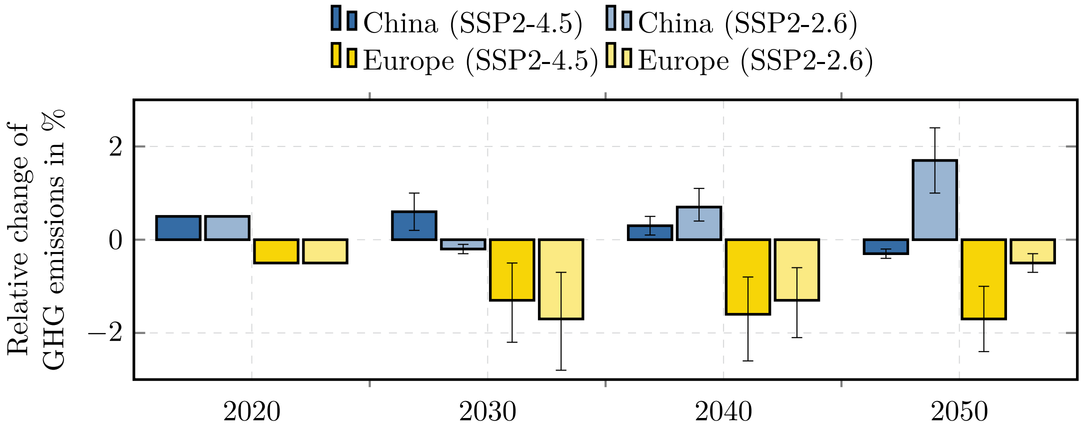


Figure 5.25: Relative changes of non-operational GHG emissions of transport due to the switch of the location of battery cell production; the spreads represent the different scenarios of the transport sector

emissions for battery production are applied in the transport scenarios. For this purpose, the corresponding values are adjusted at all locations where batteries are used. For the scenarios, the differences are thus based on the degree of electrification. The results are shown in Figure 5.25.

As can be seen, the effects on non-operational emissions are relatively minor and, with a maximum deviation of 2.8 %, can be considered low. According to the results from Figure 5.24 and Table 5.5, the changes in location can lead to more or fewer emissions. The Elec electrification scenarios show particularly strong dependencies in both positive and negative directions. In 2020, the comparatively small changes are due to the fact that few battery-electric vehicles are used in all scenarios. In the following years, the number of battery-electric vehicles increase in all scenarios, but the relevance of battery production decreases significantly compared to other vehicle parts such as the glider (also see Figure 5.23). This means that the variation of the location, despite affecting more vehicles, only addresses smaller shares of the production emissions and thus has a low level of influence on the total emissions. With a view to future prospective LCAs, other sensitivities such as the provision of steel, in particular, should thus also be investigated more closely.

5.3.5 Preliminary Summary

In the course of Chapter 5.3, the results of SDLCA were presented and discussed. The core results are summarised here. They refer to the relevance of including the upstream chain of energy carriers, the share of non-operational emissions in the analysis, and the question of the importance of the location of battery production discussed by the sensitivity analysis.

Relevance of the Upstream Chain of Energy Carriers In the current energy and transport system, the shares of upstream chain emissions are to be classified as low and the emission factor of gas increases by 24.6 % due to the integration of the upstream chain. Given the current strong linkage of hydrogen to gas in 2020, its emission factor increase of 24.6 % is in a similar range. The increase of 14.2 % for liquid hydrocarbons and 10.2 % for electricity are significantly lower. With the shift in the energy system towards renewable energies and in the transport system towards direct and indirect electrification, the relevance of the upstream chain increases considerably. In 2050, the upstream chain emissions are proportionally larger than the direct emissions in all scenarios. The increase amounts to between 592.8 % and 657.2 % of the scenarios whose focus is on indirect electrification through the use of PtX products. In the electrification scenarios, the increase is lower, and ranges from 259.0 % to 317.6 %, but can still be considered significant. The high relative increases can firstly be explained by the fact that the absolute values of direct emissions in 2050 are very low. In addition, the SDLCA methodology assigns emissions to areas that did not produce any emissions in the SDA. These areas include, for example, the construction of photovoltaic plants, which are highly relevant for both direct and indirect electrification. This in turn shows strong dependencies on the background scenarios and thus on global developments outside Europe.

Share of Non-Operational Emissions The share of non-operational emissions in 2020 is 19.2 %. This share increases in all scenarios until 2050. This shows that these emission sources, whose dependencies are only partly within the European energy system, decrease more slowly than the operational emissions. In absolute and relative terms, the non-operational emissions are higher in the electrification scenarios. This is mainly due to the additional emissions from the production of batteries. Although the shares of non-operational emissions increase, total emissions decrease and reach values of 40.5 Mt CO_2e to 81.4 Mt CO_2e by 2050. In terms of composition, it is primarily the passenger car fleet that is responsible for production emissions and hence the scenarios that pursue multimodal mobility approaches and thereby reduce the number of passenger cars achieve significantly lower emissions. Looking at the emissions of individual vehicle types in the passenger car sector, it can be concluded that significant savings can also be achieved by switching to smaller passenger car classes. In conclusion, and with a view to achieving the global climate protection goals, upstream emissions should increasingly be taken into account and the manifold possibilities for their reduction must be considered.

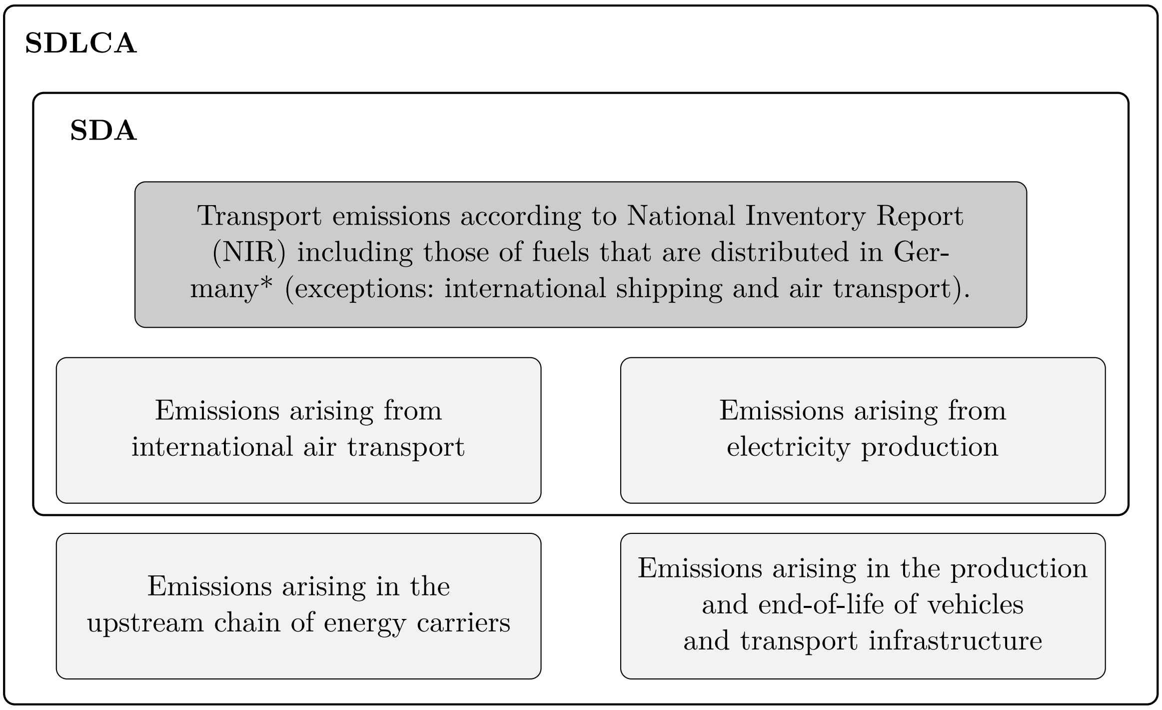
Relevance of the Location of Battery Production Large production capacities for batteries are currently being built up in Europe, which is one of the reasons why the location of battery production for the vehicles that will be on Germany's roads in the future is subject to great uncertainty. The sensitivity analysis addresses this issue by relocating the battery production of the reference case, which assumes a global mix, in two instances: once it moves completely to China and once completely to Europe. Thereby, the emissions of battery production decrease by 15.7 % when relocating to Europe in 2020. The shift to China results in an increase in emissions of 17.5 %. For Europe, the emissions also decrease in all subsequent years. The switch to China has different consequences, depending on the background scenario. For the Paris climate protection target of well below 2 °C, for example, a drastic short-term reduction in emissions in China is required, which is faster than that of the global mix. Accordingly, the switch to China reduces emissions compared to the reference case in 2030. The impact of changing the location of battery production on the total non-operational emissions of the transport sector is significantly lower. Over the entire period under consideration and in all scenarios, the switch to China leads to a maximum increase in annual emissions of 2.4 % and the switch to Europe to a reduction of 2.8 %. The small deviation is due to the fact that although the number of vehicles containing batteries increases over the period, the relevance of battery production steadily decreases. The emissions of battery production, therefore, decrease more than those of the glider. However, it must also be taken into account that the production routes of the materials used in the glider do not change in the model. Steel production, in particular, should be examined more closely in future evaluations in order to not underestimate the decline in emissions in this area.

6 Discussion of the Evaluation Methods

This chapter will compare the two methods SDA and SDLCA on a higher level. In particular, their differences in the area of system boundaries, their main limitations, the explainability of the results and the resulting suitability for recommendations for action will be addressed.

6.1 System Boundaries

The most obvious difference between the two methods SDA and SDLCA lies in their system boundaries. The SDA mainly considers the use of energy in German transport while the SDLCA includes all activities related to the German transport sector. A schematic representation of which emissions are considered in which analyses is shown in Figure 6.1.



*Difference to the presented model approach as the energy demand in the model is developed bottom-up using the vehicles.

Figure 6.1: General system boundaries of the two methods

Hence, the SDA is very similar to the allocation of emissions according to the NIR [145]. These include all emissions resulting from the combustion of fuels distributed in Germany.

Here, international shipping and air transport are exceptions, since they are not considered in the course of the NIR. Furthermore, in the SDA international air traffic and emissions from the provision of electricity are added. The electricity emissions only include the emissions released during the combustion of fossil fuels while the construction of electricity generation plants is excluded here. Another important difference between the SDA compared to the NIR is the bottom-up approach. Thus, the specific energy consumption of vehicles registered in Germany is used as the basis for calculating energy consumption. This can lead to differences compared to NIR, especially for international transport as the vehicle registration country is of no interest for the location of refuelling. In this context, international road freight transport is of particular interest. On the one hand, in the case of SDA, the energy that German vehicles refuel abroad is allocated to German emissions. On the other hand, the energy quantities refuelled by foreign vehicles in Germany are not reflected in the results. These effects are particularly relevant for Germany as an exporting nation and transit country. However, due to the lack of statistical data, quantification is not carried out in the course of this dissertation.

The SDLCA supplements the emissions of the SDA with further domains. Thus, the emissions in the upstream chain of the energy sources are supplemented which means that both the acquisition and extraction of fossil energy sources and the construction of energy conversion plants are now added. The latter is particularly interesting for renewable energy technologies such as photovoltaics and wind. In addition, emissions from the production and end-of-life of vehicles and transport infrastructure are included. Compared to the sector delimitation in NIR, emissions from other areas are relocated here. This is most easily explained by the emissions from the car industry, which were previously assigned to manufacturing industries and construction.

6.2 Major Limitations and Improvement Potentials

The most important limitations are divided into general limitations that affect both methods and a section for each method type.

General Limitations The general limitations concern those results of the model that are used for both methods. According to Chapter 5.1, this includes fleet development, energy demand, and energy supply.

A major limitation concerning the vehicle fleet relates to the division of the classes. The proportionally largest class of upper class vehicles also includes, among others, all sport utility vehicles (SUVs) and vans. Thus, this vehicle class includes vehicles with very different characteristics when it comes to driving profiles, annual mileage, and specific energy consumption. In order to evaluate certain technologies within these classes with regard to their suitability, a smaller resolution is required.

Another limitation relates to electric vehicles and their charging behaviour. Controlled charging and bi-directional charging will become increasingly relevant and will most likely be standard by 2030. The current model implementation corresponds to an ex-ante estimation of the power plant dispatch and a subsequent adaption of charging strategies. However, with the integration of electric vehicles and the corresponding charging strategies into the model environment ISAaR, cars could contribute more to an improved optimisation of the power plant dispatch than they could in the current implementation. Kern and Kigle showed that this results in a reduction in the usage of thermal power plants [148].

A further area that has the potential for a higher level of integration is the calculation of emission factors of energy carriers. Both methods use a linear approach that derives other emission factors based on the emission factor of electricity. This is done using the annual mean values. This leads to errors, especially for those technologies that pursue a cost-optimised mode of operation. Hydrogen production can be mentioned here as an example as electrolysis will increasingly be used when electricity is cheap. This is the case when the share of renewable energies is high and hence the emission factor of electricity is low. Furthermore, hydrogen might be used in thermal power plants which results in a loop that is currently not accounted for.

Finally, there is the limitation of the systemic approach in general. The chosen approach allows statements to be made about the possible positive and negative effects of certain general developments in transport. However, decisions in the context of individual transport decisions cannot be derived from this. For example, the analysis cannot provide information on which modes of transport or vehicle technologies a person should choose in order to produce the lowest possible emissions. In addition, individual circumstances such as owning a photovoltaic system or the use of green electricity for train transport can impact this decision. However, integrating these individualities would contradict the systemic approach chosen here.

Limitations of SDA The only limitation of SDA that does not also affect SDLCA relates to the exclusion of secondary effects. By neglecting emissions that are not covered in the method, it cannot be ruled out that the avoidance is not only a reallocation of emissions. By integrating the emissions of electricity production compared to NIR (also see Section 6.1), this point is largely pre-empted with regard to electric vehicles. However, the production of the vehicles represents another point of discussion that the method cannot address. This limitation also forms the basic rationale for the implementation of the SDLCA.

Limitations of SDLCA The main limitations of SDLCA result from the assumptions that have to be made. Assumptions must be made about the technology, material compositions, and production routes in addition to those derived from the development of energy demand. Furthermore, a very broad data basis is required. In order to close possible data gaps, derivations have to be made from other technologies. Thus, while the results can provide an indication of possible statements to be made, they should not be regarded as absolute values. The integration of LCA is thus a further perspective and not an increase in the level of accuracy.

As already mentioned in Chapter 4.2, LCA is an iterative method. This concept is taken into account in the SDLCA by adjusting and updating areas of particular relevance. For example, this was done for electricity and the powertrains of cars. In a further iterative improvement step, the essential process of steel supply could be analysed and adapted. In the present analysis, areas with a high steel content, such as the glider, appear to be particularly emission-intensive for future years as well. However, this conclusion would first have to be backed up with a more in-depth analysis including future steel production routes and thus cannot be drawn here. This is also true for other areas. Thus, the SDLCA serves more to provide a comprehensive understanding of the interrelationships of emissions associated with traffic than to show absolute values.

Finally, inclusion of the whole energy system with all its application sectors in the SDLCA is limited in its further conclusion. Due to the fact that emissions that are assigned to e.g. industry in other balances are also integrated into the transport sector because of the strongly extended system boundaries, the initial sector boundaries become blurred. If the emissions due to all products and services within national boundaries are to be evaluated, the approach needs to be adjusted. Starting with the emissions according to NIR, one would have to consider the foreign trade goods and subsequently subtract the emissions of exports and add those of imports.

6.3 Explainability

Especially in contexts that are close to politics and society, science communication and thus the explainability of methods and content is essential. The energy and transport transition is precisely such a context. Thus, the question arises regarding how easy the methods are to explain in order to transfer the messages correctly.

The SDA offers reasonable explainability due to its methodological similarity to the NIRs. Emissions directly associated with transport, also including those from electricity production, are easy to understand. Challenges arise in the discussion of system repercussions as well as the adjustment of the dispatch of power plants and the requirement for storage in the energy system. Particularly with regard to political decision-makers, an explanation is important so that the results are not misinterpreted. The interpretation of the model results is a fundamental challenge but can be classified as simple compared to SDLCA.

The interpretation of the SDLCA is very elaborate. Due to the many assumptions made, interrelationships only become apparent after considerable analysis of the results. The assumptions to be made also impede the explainability since the insights gained are often only valid in the context of certain assumptions. Thus, clearly stating the corresponding limitations and the associated consequences, such as the limitation of conclusions to certain applications, is a major challenge for SDLCA. This also has direct implications for the possible recommendations for action that can be derived from it.

6.4 Suitability of the Methods for Recommendations for Actions

Whether the methods offer possibilities for recommendations for action strongly depends on the addressee and the underlying question. Accordingly, a distinction is made between political representatives, company representatives, and private individuals in the following sections.

Political Representatives In the context of the methods shown, the questions posed by political representatives can be diverse. Both methods can contribute differently to the achievement of overarching goals such as the reduction of GHG emissions. Thus, due to its system boundaries and explainability, SDA can provide a good basis for recommendations for action to effectively and efficiently reduce emissions in transport and in the overall German energy system. Through the extended evaluation of costs, statements can be made regarding the cost efficiency of GHG reduction measures. However, the SDA cannot answer the question of whether this will only lead to the shift of GHG emissions abroad or in other sectors. To include this real-life perspective, SDLCA can offer guidance as a complementary method. For political representatives, this offers the opportunity to make companies aware of their supply chains abroad. Nevertheless, the SDLCA cannot be used for national emission targets, as there are strong overlaps with other sectors and countries.

Company Representatives Companies are also increasingly addressing issues in the context of environmental sustainability. In addition to their own initiative, the regulatory framework is also driving this development. For example, rising CO_2 prices are making low-emission products increasingly profitable, and the decision on the EU taxonomy is making the financing of green assets more interesting. Due to the clear sectoral separation of SDA, it can give indications of possible costs, especially in the context of CO_2 prices. However, due to the great uncertainty in the long term, precise cost information is not meaningful in the course of the scenario calculation. The SDLCA is not useful in the context of cost estimations, as possible further cost components due to emissions are not allocated to products. However, in the course of the EU taxonomy, the SDLCA can offer a relevant perspective, as the LCA method is used for emission accounting as a basis for the classification of green activities [149]. In particular, the development of the emission factors of electricity-generating technologies can serve as a classification of the suitability as a sustainable technology in the sense of the taxonomy. In addition, the reporting of Scope 2 and 3 emissions according to the GHG protocol is becoming increasingly interesting [150]. The results of the SDLCA can form an estimate of how emission factors for electricity (Scope 2) and transport services (Scope 3) can develop in the future.

Private Individuals Private individuals mainly deal with their environmental sustainability approaches out of self-interest. Thereby, questions about which mode of transport to choose or which propulsion train the car should have are of particular interest. Because of its explainability, the SDA is advantageous in this context. Its results provide a basic indication of the magnitude of emissions for different forms of transport. While the life cycle perspective of the SDLCA can also be of particular relevance for private individuals, it needs to be classified and communicated. The underlying assumptions are essential and the associated limitations restrict the suitability for recommendations.

Table 6.1 summarises the most important aspects regarding the suitability of the two methods for recommendations for action differentiated by the various target groups.

Table 6.1: Summary of the suitability for recommendations for action for certain stakeholders

	SDA	SDLCA
Political representatives	• Provides suitable context for recommendations for action in the area of sectoral and national emission reductions • Lacks an international perspective	• Not suitable for national emission reduction targets • Able to give indications of the shift of emissions to other countries due to national emission reduction measures
Company representatives	• Indicates development of additional costs due to emissions (e.g. CO_2 price) • No detailed information on the development of exact transport costs	• No statements regarding additional costs due to emissions (such as CO_2 prices) • Able to provide an input for the assessment of the eligibility of activities in terms of the EU taxonomy • Possible estimation of developments of certain scope 3 emissions
Private individuals	• Able to give a basic indication of the emissions related to the choice of transport form due to good explainability	• Additional life cycle perspective, especially for passenger cars, but needs classification and simplification due to many assumptions

7 Conclusion and Outlook

In the course of the dissertation, a model was developed to represent the German transport sector embedded in a dynamic European energy system. The model was used for ecological assessment by means of the methods of SDA and SDLCA, which address the development of GHG emissions from two different perspectives. The results of the modelling that was carried out and the two methods were compared and differences identified. In the following, the answers to the research questions as well as a critical reflection and research outlook are provided.

7.1 Answers to the Research Questions

The work in the course of the dissertation was designed to address the research questions from Chapter 1.3. Their answers are summarised in the following.

How can the transport sector be modelled in the context of a dynamic energy system? In order to model the transport sector with its dynamics embedded in the energy system, a bottom-up approach is needed. This means that the sector has to be modelled starting from its elements, i.e. vehicles. The energy demand is derived on the basis of the individual types. Especially in the context of the increasing electricity demand of the transport sector, the temporal resolution of the energy demand of the elements of transport is of growing relevance. The characteristics of the bottom-up approach also enable the implementation of measures and the addition of the costs of the transport sector, which include not only energy costs but also investment costs and costs for maintenance and repair. The changes in the fleet composition are realised through the implementation as a stock-and-flow model. Therefore, it calculates the development of the stock of the fleet via the historical stock as well as commissionings and decommissionings which ensures that transition rates are not overestimated. One of the greatest challenges is to keep the quality of the broad data base required as consistent as possible. Nevertheless, to be able to elicit possible compromises in terms of the level of detail, it is advisable to carry out an initial estimation of energy consumption and the associated emissions in the context of the underlying research questions. Finally, the model allows the derivation of emission factors for electricity and hydrogen next to those directly arising at the tailpipe due to the combustion of hydrocarbons. This is a prerequisite for the evaluation of energy-related emissions in the scenarios. Finally, emission factors for energy carriers from energy system modelling also allow for the assessment of energy-related emissions. These include emissions from direct combustion as well as those resulting from the provision of electricity and hydrogen in the energy system.

What challenges arise with the integration of life cycle assessment in transport sector modelling and how they can be addressed? When integrating the life cycle perspective, the emissions of the conventional energy system modelling approach are expanded to include those that arise from the production and end-of-life of the vehicles and emissions from the upstream chain of energy sources. In this respect, the bottom-up approach of the transport sector model is a prerequisite, as the years of commissioning and decommissioning have to be known for each element of the sector. The vehicles have to be provided with emission factors for the corresponding life cycle phases in the particular years. In order to create this extensive database, the open source models premise and carculator were used. These make it possible to map a large part of the required vehicles and adapt their future production and end-of-life processes based on the ecoinvent database. The adjustments were made with a focus on the German transport sector and additional vehicles that were not included in the open source models or in ecoinvent were added from further literature. The creation of the simultaneously required database represents one of the greatest challenges and also still offers great potential for improvement. For the upstream chain of energy supply, premise was also used, particularly to map the development of the production of renewable energy technologies such as photovoltaics and wind turbines. In this context, it is important to ensure the consistency of the background scenarios for the LCA of the energy conversion technologies with those of the energy system modelling.

How does the development of the transport sector affect the goal of a drastic reduction of GHG emissions in the whole energy system? Coupling the modelling of the transport sector with the energy system enables the investigation of the repercussions of the respective sectors on each other. Thereby, the framework conditions which are exogenously set are essential. In the present dissertation, scenarios were investigated whose goal is to achieve the reduction of GHG emissions throughout Europe in accordance with the 2 °C emission reduction target. Two scenarios were modelled in which large proportions of hydrocarbons are still required by 2050, and two scenarios in which large parts of road traffic are electrified and thus the total demand for hydrocarbons is greatly reduced. In all scenarios, a large expansion of renewable energy technologies was needed by 2030. This was especially the case if there was no rapid electrification in the transport sector, as this shifted the required emission reduction to the supply sector. The use of synthetic fuels did not play a role until 2030 because their costs were too high. From 2040 onwards, synthetic fuels were used in the scenarios that continued to rely on large shares of hydrocarbons. The scenarios in which the transport sector was largely electrified did not require synthetic fuels to achieve the emission cap by 2050. In summary, it can be said that a reduction in the combustion of hydrocarbons leads to a decrease in the burden of the overall system. However, if large quantities of hydrocarbons continue to produce emissions in transport, the emission reduction needs to occur in the supply sector. Due to lower costs, it is preferable that renewable energies are expanded first before synthetic fuels, which result in negative emissions in the supply sector, are introduced.

What additional emissions arise in the assessment through the integration of a life cycle perspective and how might this develop in the future? The extension of the assessment to include a life cycle perspective has two main aspects: the addition of upstream emissions from the energy sources used and the integration of non-operational emissions from the production and end-of-life phase of the vehicles in the transport system. Considering upstream chain emissions in the current transport system, the additional emissions are considered as being low. The increase in 2020 was assessed at 10.2 % for electricity, 14.2 % for liquid hydrocarbons, 24.6 % for hydrogen, and 26.2 % for natural gas. However, since almost only liquid hydrocarbons are used, the emissions in the entire transport sector increase by 14.3 %. Nevertheless, with the reduction of direct emissions in the years following, the relevance of the upstream chain increases significantly. In the scenarios with large shares of synthetic fuels, the increase reached up to 657.2 %. In scenarios in which large shares of transport are electrified, the increase is significantly lower at a maximum of 317.6 %, but still substantial. The large increases can be attributed to the fact that the integration of the upstream chain attributes GHG emissions to renewable energy technologies that previously did not have any emission factors. The efficiency chain of synthetic fuels ensures that the increase in their use is significantly higher than in the more efficient direct use of electricity. The large increase in emissions through the integration of the upstream chain, particularly in scenarios that directly or indirectly use a large share of renewable electricity, leads to the conclusion that a life cycle perspective is essential in this context as it ensures that all associated emissions of the transport systems to be evaluated are included. The non-operational emissions in the evaluation amounted to 47.6 Mt CO_2e in 2020 and thus 19.2 % of total emissions. The absolute non-operational emissions subsequently decrease in the scenarios. However, their share of total emissions increases. This is more evident in the scenarios with many electrified vehicles, as their production will continue to be associated with more emissions than that of conventional vehicles. In the case in which a global scenario is chosen that does not pursue a 2 ℃ target, the share is higher, as individual parts of vehicle production are also produced in countries outside Europe. The most important share of non-operational emissions of the transport fleet was in the production of passenger cars. In particular, the production of vehicle gliders accounted for the largest share. Therefore, switching battery production to other, less emission-intensive countries leads to a noticeable reduction in battery emissions although the impact on total non-operational emissions was found to be small.

How do the two methods of emissions accounting differ and for what purpose can they be considered? The two methods presented, SDA and SDLCA, differ in their system boundaries, major limitations, explainability, and suitability for recommendations for action. The system boundaries of SDA are similar to those of conventional emissions reporting (e.g. NIR), while SDLCA draws much wider boundaries. In the course of SDLCA, emissions are added to the transport sector, which are allocated to the energy or industry sector in other emission accounting methods. The limitations and the explainability of both methods indirectly relate to their system boundaries. The SDA neglects secondary effects and thus disregards possible shifts of emissions to other sectors and countries. However, the narrow system boundaries ensure simple explainability. In the case of SDLCA, due to its wide system boundaries, assumptions must be made in many areas which subsequently limit the validity of certain statements. Thus, it is essential to classify the results in the context of the assumptions. The most important assumptions in the presented scenarios relate to the vehicle and battery sizes, the specific consumption levels, and the origin of the energy carriers electricity and synthetic fuels. With regard to the suitability of recommendations for action, it can be summarised that, due to its extended perspective, the SDLCA is able to offer interesting perspectives for sustainably committed companies and private individuals. However, the method is not suitable for providing recommendations for action in the area of national emission targets. This is in contrast to the SDA, which is highly suitable for national targets due to its system boundaries, but thereby also neglects international developments.

7.2 Critical Reflection and Research Outlook

In the course of this dissertation, constant reference was drawn to the underlying assumptions and their effects on the evaluation. The viability of the assumptions strongly depends on the research question and thus the results are not always generalizable. In particular, the major limitations in Chapter 6.2 show that further research is needed in the area of transport emission modelling. Three of the aspects that were particularly noticeable in the course of the dissertation are now presented in the following and possible approaches for further research are formulated.

Integration of the Derivation of Emission Factors into the Energy System Model By the end of this dissertation, the emission factors for the energy carriers are derived ex-post from the results of the energy system model. The factors of the other energy carriers are calculated based on the emission factor of electricity. This leads to the fact that possible mutual influences from the provision of the energy carriers, such as the use of hydrogen for the production of electricity, cannot be represented. Thus, the emission factors for hydrogen do not reflect the fact that electrolyzers are favoured to produce hydrogen at those hours during which low electricity prices are available. Since this is the case when the production of renewable energies and therefore their share is high, the resulting emission factor for hydrogen would be lower. To solve this problem, the emission factor calculation must be integrated into the energy system ISAaR. Similar to the calculation of the costs for energy carriers, this could also be used to evaluate operational strategies of energy conversion technologies and to map the use of energy storage. In addition, the imported and exported emissions of energy carriers from individual countries could be depicted in more detail.

Stronger Integration of the Results of the European Energy System Modelling into the Global Background Scenarios The composition of the electricity supply is one of the results derived from the European energy system modelling. The results serve as an input for the background scenarios, which include the global energy supply in spatial resolution and which are needed for the derivation of the life cycle perspective. Further energy carriers and transport services derived from transport modelling are not used as an input for the background scenarios. To give an example, the reduction of operational emissions in transport indirectly leads to a reduction of non-operational emissions, as transport activities are also accounted for in the upstream chains of production. In addition, it would be possible to take into account more precise time determination in the parts of the upstream chains of non-operational emissions. This form of integration has not yet taken place and the corresponding effort is estimated to be very high. Nevertheless, it is assumed that the value of the insights to be gained in both the energy system modelling community and the LCA community could be great.

Focus on the Glider and its Materials in prospective LCA Past LCAs have often dealt with the comparison of ICEVs and BEVs and thus mostly focused on the battery as the most important additional cost in production. Especially for prospective LCAs, however, one should focus more on development in the production of the glider. For example, in the present dissertation, no process route change took place for steel production. Nevertheless, it can be assumed that in the future steel will increasingly be produced with the help of electricity or hydrogen. Therefore, future LCAs would change fundamentally with the integration of these developments.

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A Annex

A.1 Scenario Data

Table A.1: Share of multimodal people in the scenario Multi age group, derived from mobility statistics [40]

Age group	**2020**	**2030**	**2040**	**2050**
16 - 19 years	56.0 %	67.0 %	81.0 %	97.0 %
20 - 29 years	39.0 %	58.8 %	70.6 %	84.7 %
30 - 39 years	36.0 %	41.0 %	61.7 %	74.1 %
40 - 49 years	38.0 %	37.8 %	43.0 %	64.8 %
50 - 49 years	37.0 %	39.9 %	39.7 %	45.2 %
60 - 49 years	36.0 %	38.9 %	41.9 %	41.7 %
Average	38.2 %	44.3 %	52.3 %	63.0 %

Table A.2: Share of multimodal people in the scenario Multi by type of region they live in, derived from mobility statistics [40]

Region type	**2020**	**2030**	**2040**	**2050**
Metropolis	47.0 %	63.5 %	79.1 %	92.0 %
Regiopolis	39.5 %	46.5 %	58.0 %	74.9 %
Mid-size city	39.5 %	46.5 %	58.0 %	74.9 %
Rural area	32.5 %	32.5 %	32.5 %	32.5 %

Table A.3: Share of technologies in commissionings of privately used passenger transport by vehicle type in the technology scenario CoHC based on Schlesinger et al. [73]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Small car	Petrol ICEV	41	36	16	0
Small car	Diesel ICEV	38	29	31	24
Small car	LPG ICEV	1	1	1	1
Small car	CNG ICEV	6	11	15	22
Small car	HEV	6	10	15	22
Small car	BEV	5	8	12	17
Small car	PHEV	3	4	7	10
Small car	FCEV	0	1	3	4
Compact car	Petrol ICEV	41	36	16	0
Compact car	Diesel ICEV	38	29	31	24
Compact car	LPG ICEV	1	1	1	1
Compact car	CNG ICEV	6	11	15	22
Compact car	HEV	6	10	15	22
Compact car	BEV	5	8	12	17
Compact car	PHEV	3	4	7	10
Compact car	FCEV	0	1	3	4
Medium car	Petrol ICEV	41	36	16	0
Medium car	Diesel ICEV	38	29	31	24
Medium car	LPG ICEV	1	1	1	1
Medium car	CNG ICEV	6	11	15	22
Medium car	HEV	6	10	15	22
Medium car	BEV	5	8	12	17
Medium car	PHEV	3	4	7	10
Medium car	FCEV	0	1	3	4
Upper class car	Petrol ICEV	41	36	16	0
Upper class car	Diesel ICEV	38	29	31	24
Upper class car	LPG ICEV	1	1	1	1
Upper class car	CNG ICEV	6	11	15	22
Upper class car	HEV	6	10	15	22
Upper class car	BEV	5	8	12	17
Upper class car	PHEV	3	4	7	10
Upper class car	FCEV	0	1	3	4
Motorcycle	Petrol ICEV	86	52	36	19
Motorcycle	BEV	14	48	64	81

Table A.4: Share of technologies in commissionings of privately used passenger transport by vehicle type in the technology scenario Elec based on Conrad et al. [9]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Small car	Petrol ICEV	30	11	0	0
Small car	Diesel ICEV	27	8	0	0
Small car	LPG ICEV	1	0	0	0
Small car	CNG ICEV	4	3	7	4
Small car	HEV	4	3	7	4
Small car	BEV	31	70	76	79
Small car	PHEV	3	4	7	10
Small car	FCEV	0	1	3	4
Compact car	Petrol ICEV	30	13	0	0
Compact car	Diesel ICEV	27	10	2	0
Compact car	LPG ICEV	1	0	0	0
Compact car	CNG ICEV	4	4	8	6
Compact car	HEV	4	4	8	6
Compact car	BEV	31	64	73	75
Compact car	PHEV	3	4	7	10
Compact car	FCEV	0	1	3	4
Medium car	Petrol ICEV	28	20	0	0
Medium car	Diesel ICEV	25	15	8	0
Medium car	LPG ICEV	1	1	0	0
Medium car	CNG ICEV	4	6	6	5
Medium car	HEV	4	6	6	5
Medium car	BEV	35	35	54	50
Medium car	PHEV	3	4	7	10
Medium car	FCEV	2	14	19	30
Upper class car	Petrol ICEV	37	15	2	0
Upper class car	Diesel ICEV	34	11	8	0
Upper class car	LPG ICEV	1	0	0	0
Upper class car	CNG ICEV	6	11	15	22
Upper class car	HEV	5	4	5	0
Upper class car	BEV	12	41	40	53
Upper class car	PHEV	3	4	7	10
Upper class car	FCEV	2	14	23	15
Motorcycle	Petrol ICEV	72	41	28	12
Motorcycle	BEV	28	59	72	88

Table A.5: Share of technologies in commissionings of different vehicle types within each transport type in the technology scenario CoHC based on Conrad et al. [9]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
LDV	Petrol ICEV	5	3	2	0
LDV	Diesel ICEV	93	93	92	92
LDV	LPG ICEV	1	1	1	1
LDV	CNG ICEV	2	3	4	6
LDV	BEV	0	0	0	1
LDV	FCEV	0	0	0	0
MDV	Petrol ICEV	0	0	0	0
MDV	Diesel ICEV	100	100	100	100
MDV	LPG ICEV	0	0	0	0
MDV	CNG ICEV	0	0	0	0
MDV	BEV	0	0	0	0
MDV	FCEV	0	0	0	0
HDV	Diesel ICEV	100	100	100	100
HDV	CNG ICEV	0	0	0	0
HDV	BEV	0	0	0	0
HDV	FCEV	0	0	0	0
Semi-trailer	Diesel ICEV	100	100	100	100
Semi-trailer	CNG ICEV	0	0	0	0
Semi-trailer	BEV	0	0	0	0
Semi-trailer	BEV OCST	0	0	0	0
Semi-trailer	FCEV	0	0	0	0
Freight train	Diesel ICEV	5	5	4	4
Freight train	Electric drive	95	95	96	96
Local train	Diesel ICEV	24	24	24	24
Local train	Electric drive	76	76	76	76
Long-distance train	Diesel ICEV	8	8	8	8
Long-distance train	Electric drive	92	92	92	92
High-speed train	Electric drive	100	100	100	100
Inner city train	Electric drive	100	100	100	100
Vessel	Diesel ICEV	100	100	100	100
Vessel	FCEV	0	0	0	0
Aircraft (domestic)	Turbine	100	100	100	100
Aircraft (internat.)	Turbine	100	100	100	100

Table A.6: Share of technologies in commissionings of different vehicle types within each transport type in the technology scenario Elec based on Conrad et al. [9]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
LDV	Petrol ICEV	2	1	0	0
LDV	Diesel ICEV	65	28	35	20
LDV	LPG ICEV	1	0	1	1
LDV	CNG ICEV	2	1	3	2
LDV	BEV	30	70	62	77
LDV	FCEV	0	0	0	0
MDV	Petrol ICEV	0	0	0	0
MDV	Diesel ICEV	78	43	46	21
MDV	LPG ICEV	0	0	0	0
MDV	CNG ICEV	0	0	0	0
MDV	BEV	22	23	26	29
MDV	FCEV	0	34	28	50
HDV	Diesel ICEV	73	38	35	15
HDV	CNG ICEV	27	33	37	44
HDV	BEV	0	14	13	20
HDV	FCEV	0	15	14	21
Semi-trailer	Diesel ICEV	83	40	31	26
Semi-trailer	CNG ICEV	0	0	0	0
Semi-trailer	BEV	6	18	19	18
Semi-trailer	BEV OCST	11	37	38	37
Semi-trailer	FCEV	0	5	12	19
Freight train	Diesel ICEV	0	0	0	0
Freight train	Electric drive	100	100	100	100
Local train	Diesel ICEV	0	0	0	0
Local train	Electric drive	100	100	100	100
Long-distance train	Diesel ICEV	0	0	0	0
Long-distance train	Electric drive	100	100	100	100
High-speed train	Electric drive	100	100	100	100
Inner city train	Electric drive	100	100	100	100
Vessel	Diesel ICEV	50	50	50	50
Vessel	FCEV	50	50	50	50
Aircraft (domestic)	Turbine	100	100	100	100
Aircraft (internat.)	Turbine	100	100	100	100

Table A.7: Share of technologies in commissionings of buses within each transport type in the technology scenario CoHC based on Schlesinger et al. [73]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Bus (12 seats)	Petrol ICEV	0	0	0	0
Bus (12 seats)	Diesel ICEV	91	85	76	64
Bus (12 seats)	CNG ICEV	8	12	20	30
Bus (12 seats)	BEV	1	2	4	6
Bus (12 seats)	FCEV	0	0	0	0
Bus (24 seats)	Petrol ICEV	0	0	0	0
Bus (24 seats)	Diesel ICEV	91	85	76	64
Bus (24 seats)	CNG ICEV	7	11	18	27
Bus (24 seats)	BEV	2	3	6	9
Bus (24 seats)	FCEV	0	0	0	0
Bus (36 seats)	Petrol ICEV	0	0	0	0
Bus (36 seats)	Diesel ICEV	80	70	56	41
Bus (36 seats)	CNG ICEV	15	23	33	45
Bus (36 seats)	BEV	5	7	10	14
Bus (36 seats)	FCEV	0	0	0	0
Bus (45 seats)	Petrol ICEV	0	0	0	0
Bus (45 seats)	Diesel ICEV	79	68	54	39
Bus (45 seats)	CNG ICEV	12	18	26	34
Bus (45 seats)	BEV	9	14	20	27
Bus (45 seats)	FCEV	0	0	0	0
Bus (55 seats)	Petrol ICEV	0	0	0	0
Bus (55 seats)	Diesel ICEV	97	95	92	86
Bus (55 seats)	CNG ICEV	3	5	8	13
Bus (55 seats)	BEV	0	0	1	1
Bus (55 seats)	FCEV	0	0	0	0
Bus (65 seats)	Petrol ICEV	0	0	0	0
Bus (65 seats)	Diesel ICEV	100	100	100	100
Bus (65 seats)	CNG ICEV	0	0	0	0
Bus (65 seats)	BEV	0	0	0	0
Bus (65 seats)	FCEV	0	0	0	0
Bus (83 seats)	Petrol ICEV	0	0	0	0
Bus (83 seats)	Diesel ICEV	98	96	93	88
Bus (83 seats)	CNG ICEV	2	4	7	12
Bus (83 seats)	BEV	0	0	0	0
Bus (83 seats)	FCEV	0	0	0	0

Table A.8: Share of technologies in commissionings of buses within each transport type in the technology scenario Elec based on Conrad et al. [9]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Bus (12 seats)	Petrol ICEV	0	0	0	0
Bus (12 seats)	Diesel ICEV	0	0	0	0
Bus (12 seats)	CNG ICEV	0	0	0	0
Bus (12 seats)	BEV	100	100	100	100
Bus (12 seats)	FCEV	0	0	0	0
Bus (24 seats)	Petrol ICEV	0	0	0	0
Bus (24 seats)	Diesel ICEV	69	19	0	0
Bus (24 seats)	CNG ICEV	5	3	3	2
Bus (24 seats)	BEV	26	79	97	98
Bus (24 seats)	FCEV	0	0	0	0
Bus (36 seats)	Petrol ICEV	0	0	0	0
Bus (36 seats)	Diesel ICEV	68	39	27	3
Bus (36 seats)	CNG ICEV	13	13	22	23
Bus (36 seats)	BEV	19	48	52	74
Bus (36 seats)	FCEV	0	0	0	0
Bus (45 seats)	Petrol ICEV	0	0	0	0
Bus (45 seats)	Diesel ICEV	71	49	35	15
Bus (45 seats)	CNG ICEV	11	13	20	23
Bus (45 seats)	BEV	18	38	45	62
Bus (45 seats)	FCEV	0	0	0	0
Bus (55 seats)	Petrol ICEV	0	0	0	0
Bus (55 seats)	Diesel ICEV	85	57	47	6
Bus (55 seats)	CNG ICEV	2	3	5	6
Bus (55 seats)	BEV	12	40	48	87
Bus (55 seats)	FCEV	0	0	0	0
Bus (65 seats)	Petrol ICEV	0	0	0	0
Bus (65 seats)	Diesel ICEV	0	0	0	0
Bus (65 seats)	CNG ICEV	0	0	0	0
Bus (65 seats)	BEV	100	100	100	100
Bus (65 seats)	FCEV	0	0	0	0
Bus (83 seats)	Petrol ICEV	0	0	0	0
Bus (83 seats)	Diesel ICEV	0	0	0	0
Bus (83 seats)	CNG ICEV	0	0	0	0
Bus (83 seats)	BEV	100	100	100	100
Bus (83 seats)	FCEV	0	0	0	0

Table A.9: Share of technologies in commissionings of coaches within each transport type in the technology scenario CoHC based on Schlesinger et al. [73]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Coach (55 seats)	Petrol ICEV	0	0	0	0
Coach (55 seats)	Diesel ICEV	100	100	100	100
Coach (55 seats)	CNG ICEV	0	0	0	0
Coach (55 seats)	BEV	0	0	0	0
Coach (55 seats)	FCEV	0	0	0	0
Coach (83 seats)	Petrol ICEV	0	0	0	0
Coach (83 seats)	Diesel ICEV	100	100	100	100
Coach (83 seats)	CNG ICEV	0	0	0	0
Coach (83 seats)	BEV	0	0	0	0
Coach (83 seats)	FCEV	0	0	0	0

Table A.10: Share of technologies in commissionings of coaches within each transport type in the technology scenario Elec based on Conrad et al. [9]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Coach (55 seats)	Petrol ICEV	0	0	0	0
Coach (55 seats)	Diesel ICEV	100	0	0	0
Coach (55 seats)	CNG ICEV	0	0	0	0
Coach (55 seats)	BEV	0	100	100	100
Coach (55 seats)	FCEV	0	0	0	0
Coach (83 seats)	Petrol ICEV	0	0	0	0
Coach (83 seats)	Diesel ICEV	100	0	0	0
Coach (83 seats)	CNG ICEV	0	0	0	0
Coach (83 seats)	BEV	0	100	100	100
Coach (83 seats)	FCEV	0	0	0	0

Table A.11: Share of technologies in commissionings of shared vehicles within each transport type in both technology scenarios based on Gyetko [57]

		Share of commissionings within transport type in %			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Car sharing vehicle	Petrol ICEV	33	21	7	0
Car sharing vehicle	Diesel ICEV	25	18	7	0
Car sharing vehicle	BEV	38	54	75	87
Car sharing vehicle	PHEV	4	6	9	10
Car sharing vehicle	FCEV	0	0	2	4

A.2 Techno-Economic Data of Vehicles Types in Transport

Table A.12: Specific energy consumption of privately used passenger transport by vehicle type in 2020 and 2050

		Specific energy consumption in kWh/km		
Transport type	**Vehicle type**	**2020**	**2050**	**References**
Small car	Petrol ICEV	0.511	0.426	[105, 106]
Small car	Diesel ICEV	0.419	0.326	[105, 106]
Small car	LPG ICEV	0.511	0.426	[105, 106]
Small car	CNG ICEV	0.494	0.414	[105, 106]
Small car	HEV	0.363	0.292	[105, 106]
Small car	BEV	0.155	0.114	[105, 106]
Small car	PHEV	0.205	0.165	[105, 106]
Small car	FCEV	0.283	0.213	[105, 106]
Compact car	Petrol ICEV	0.589	0.491	[105, 106]
Compact car	Diesel ICEV	0.508	0.395	[105, 106]
Compact car	LPG ICEV	0.589	0.491	[105, 106]
Compact car	CNG ICEV	0.570	0.477	[105, 106]
Compact car	HEV	0.418	0.336	[105, 106]
Compact car	BEV	0.175	0.129	[105, 106]
Compact car	PHEV	0.312	0.251	[105, 106]
Compact car	FCEV	0.320	0.240	[105, 106]
Medium car	Petrol ICEV	0.611	0.510	[105, 106]
Medium car	Diesel ICEV	0.539	0.420	[105, 106]
Medium car	LPG ICEV	0.611	0.510	[105, 106]
Medium car	CNG ICEV	0.591	0.496	[105, 106]
Medium car	HEV	0.434	0.349	[105, 106]
Medium car	BEV	0.185	0.136	[105, 106]
Medium car	PHEV	0.365	0.295	[105, 106]
Medium car	FCEV	0.338	0.254	[105, 106]
Upper class car	Petrol ICEV	0.685	0.571	[105, 106]
Upper class car	Diesel ICEV	0.661	0.515	[105, 106]
Upper class car	LPG ICEV	0.685	0.571	[105, 106]
Upper class car	CNG ICEV	0.663	0.555	[105, 106]
Upper class car	HEV	0.486	0.391	[105, 106]
Upper class car	BEV	0.230	0.169	[105, 106]
Upper class car	PHEV	0.368	0.297	[105, 106]
Upper class car	FCEV	0.421	0.315	[105, 106]
Motorcycle	Petrol ICEV	0.538	0.106	[59, 105]
Motorcycle	BEV	0.494	0.095	[59, 105]

Table A.13: Specific energy consumption of different vehicles by vehicle type in 2020 and 2050

		Specific energy consumption in kWh/km		
Transport type	**Vehicle type**	**2020**	**2050**	**References**
LDV	Petrol ICEV	1.346	1.191	[105]
LDV	Diesel ICEV	0.860	0.710	[105]
LDV	LPG ICEV	1.346	1.191	[105]
LDV	CNG ICEV	1.220	1.030	[105]
LDV	BEV	0.300	0.220	[105]
LDV	FCEV	0.520	0.430	[105]
MDV	Petrol ICEV	2.441	2.222	[105]
MDV	Diesel ICEV	1.560	1.420	[105]
MDV	LPG ICEV	2.441	2.222	[105]
MDV	CNG ICEV	2.250	1.890	[105]
MDV	BEV	0.750	0.663	[105]
MDV	FCEV	1.080	0.887	[105]
HDV	Diesel ICEV	2.177	2.055	[64, 105]
HDV	CNG ICEV	3.139	2.735	[64, 105]
HDV	BEV	1.344	0.959	[64, 105]
HDV	FCEV	2.497	1.284	[64, 105]
Semi-trailer	Diesel ICEV	2.980	2.380	[108]
Semi-trailer	CNG ICEV	3.225	2.380	[108]
Semi-trailer	BEV	1.570	1.420	[108]
Semi-trailer	BEV OCST	1.675	1.510	[108]
Semi-trailer	FCEV	2.510	2.090	[108]
Freight train	Diesel ICEV	50.972	48.605	Own assumption based on expert interviews and adjusted with [59]
Freight train	Electric drive	15.966	14.919	
Local train	Diesel ICEV	28.252	28.252	
Local train	Electric drive	8.428	8.428	
Long-distance train	Diesel ICEV	34.159	34.159	
Long-distance train	Electric drive	8.967	8.967	
High-speed train	Electric drive	17.135	17.135	
Inner city train	Electric drive	5.600	5.300	
Vessel	Diesel ICEV	76.522	76.522	[73, 109]
Vessel	FCEV	66.957	66.957	[73, 109]
Aircraft (domestic)	Turbine	73.121	50.867	[62, 73]
Aircraft (internat.)	Turbine	123.090	89.885	[62, 73]

Table A.14: Specific energy consumption of buses by vehicle type in 2020 and 2050

		Specific energy consumption in kWh/km		
Transport type	**Vehicle type**	**2020**	**2050**	**References**
Bus (12 seats)	Petrol ICEV	1.935	1.591	Own assumption based on [59, 73, 110]
Bus (12 seats)	Diesel ICEV	1.237	1.017	
Bus (12 seats)	CNG ICEV	1.300	1.192	
Bus (12 seats)	BEV	0.524	0.473	
Bus (12 seats)	FCEV	0.908	0.820	
Bus (24 seats)	Petrol ICEV	3.871	3.183	Own assumption based on [59, 73, 110]
Bus (24 seats)	Diesel ICEV	2.473	2.034	
Bus (24 seats)	CNG ICEV	2.599	2.384	
Bus (24 seats)	BEV	1.048	0.947	
Bus (24 seats)	FCEV	1.816	1.641	
Bus (36 seats)	Petrol ICEV	5.806	4.774	Own assumption based on [59, 73, 110]
Bus (36 seats)	Diesel ICEV	3.710	3.050	
Bus (36 seats)	CNG ICEV	3.899	3.576	
Bus (36 seats)	BEV	1.572	1.420	
Bus (36 seats)	FCEV	2.724	2.462	
Bus (45 seats)	Petrol ICEV	7.257	5.967	Own assumption based on [59, 73, 110]
Bus (45 seats)	Diesel ICEV	4.637	3.813	
Bus (45 seats)	CNG ICEV	5.465	5.012	
Bus (45 seats)	BEV	1.961	1.772	
Bus (45 seats)	FCEV	3.400	3.072	
Bus (55 seats)	Petrol ICEV	8.870	7.294	Own assumption based on [59, 73, 110]
Bus (55 seats)	Diesel ICEV	5.667	4.660	
Bus (55 seats)	CNG ICEV	5.956	5.463	
Bus (55 seats)	BEV	2.401	2.170	
Bus (55 seats)	FCEV	4.162	3.761	
Bus (65 seats)	Petrol ICEV	10.483	8.620	Own assumption based on [59, 73, 110]
Bus (65 seats)	Diesel ICEV	6.698	5.507	
Bus (65 seats)	CNG ICEV	7.039	6.456	
Bus (65 seats)	BEV	2.838	2.564	
Bus (65 seats)	FCEV	4.919	4.444	
Bus (83 seats)	Petrol ICEV	13.386	11.007	Own assumption based on [59, 73, 110]
Bus (83 seats)	Diesel ICEV	8.553	7.033	
Bus (83 seats)	CNG ICEV	9.519	8.730	
Bus (83 seats)	BEV	3.624	3.274	
Bus (83 seats)	FCEV	6.281	5.675	

Table A.15: Specific energy consumption of coaches by vehicle type in 2020 and 2050

Transport type	**Vehicle type**	**Specific energy consumption in kWh/km 2020**	**2050**	**References**
Coach (55 seats)	Petrol ICEV	4.489	2.774	Own assumption based on [59, 73, 110]
Coach (55 seats)	Diesel ICEV	2.868	1.772	
Coach (55 seats)	CNG ICEV	2.797	1.728	
Coach (55 seats)	BEV	1.151	0.884	
Coach (55 seats)	FCEV	1.996	1.532	
Coach (83 seats)	Petrol ICEV	6.777	4.187	Own assumption based on [59, 73, 110]
Coach (83 seats)	Diesel ICEV	4.330	2.675	
Coach (83 seats)	CNG ICEV	4.223	2.609	
Coach (83 seats)	BEV	1.731	1.329	
Coach (83 seats)	FCEV	3.001	2.304	

Table A.16: Capacity factors, annual mileages and average lifetimes of the transport types of the model based on Conrad et al. and Gyetko [9, 57]

Transport type	**Capacity factor in $\frac{pkm}{km}$ or $\frac{tkm}{km}$**	**Annual mileage in km**	**Average lifetime in a**
Small car (private)	1.5	11,050	12.8
Compact car (private)	1.5	12,797	12.8
Medium car (private)	1.5	14,654	12.8
Upper class car (private)	1.5	16,678	12.8
Small car (shared, FF)	2.0	28,000	4
Compact car (shared, FF)	2.0	28,000	4
Medium car (shared, FF)	2.0	28,000	4
Upper class car (shared, FF)	2.0	28,000	4
Small car (shared, SB)	1.6	28,000	4
Compact car (shared, SB)	1.6	28,000	4
Medium car (shared, SB)	1.6	28,000	4
Upper class car (shared, SB)	1.6	28,000	4
LDV	1.2	21,711	11
MDV	8.1	38,816	11
HDV	8.3	38,816	10
Semi-trailer	17.1	113,914	6
Bus (12 seats)	4.0	38,126	12
Bus (24 seats)	8.0	38,126	12
Bus (36 seats)	12.0	38,126	12
Bus (45 seats)	15.0	38,126	12
Bus (55 seats)	18.3	38,126	12
Bus (65 seats)	21.7	38,126	12
Bus (83 seats)	27.6	38,126	12
Coach (55 seats)	33.5	174,538	12
Coach (83 seats)	50.5	174,538	12
Motorcycle	1.0	3,020	15
Freight train	532.3	109,165	25
Local train	91.0	151,199	40
Long-distance train	203.8	209,343	40
High-speed train	361.1	314,015	40
Inner city train	54.7	48,091	40
Vessel	1,259	19,636	47
Passenger flight (domestic)	87.7	2,235,000	25
Passenger flight (intern.)	238.2	2,235,000	25
Air freight (domestic)	9.1	2,235,000	25
Air freight (intern.)	24.3	2,235,000	25

Table A.17: Transport and vehicle types modelled in the transport model

Transport carrier	**Transport type**	P-ICEV	D-ICEV	CNG-ICEV	LPG-ICEV	HEV	BEV	PHEV	FCEV	Turbine
Street	Small car (private)	X	X	X	X	X	X	X	X	
Street	Compact car (private)	X	X	X	X	X	X	X	X	
Street	Medium car (private)	X	X	X	X	X	X	X	X	
Street	Upper class car (private)	X	X	X	X	X	X	X	X	
Street	Small car (shared, FF)	X	X				X	X	X	
Street	Compact car (shared, FF)	X	X				X	X	X	
Street	Medium car (shared, FF)	X	X				X	X	X	
Street	Upper class car (shared, FF)	X	X				X	X	X	
Street	Small car (shared, SB)	X	X				X	X	X	
Street	Compact car (shared, SB)	X	X				X	X	X	
Street	Medium car (shared, SB)	X	X				X	X	X	
Street	Upper class car (shared, SB)	X	X				X	X	X	
Street	LDV	X	X	X	X	X	X		X	
Street	MDV	X	X	X	X	X	X		X	
Street	HDV		X	X			X		X	
Street	Semi-trailer		X	X			X[*]		X	
Street	Bus (12 seats)	X	X	X			X		X	
Street	Bus (24 seats)	X	X	X			X		X	
Street	Bus (36 seats)	X	X	X			X		X	
Street	Bus (45 seats)	X	X	X			X		X	
Street	Bus (55 seats)	X	X	X			X		X	
Street	Bus (65 seats)	X	X	X			X		X	
Street	Bus (83 seats)	X	X	X			X		X	
Street	Coach (55 seats)	X	X	X			X		X	
Street	Coach (83 seats)	X	X	X			X		X	
Street	Motorcycle	X					X			
Rail	Freight train		X				X			
Rail	Local train		X				X			
Rail	Long-distance train		X				X			
Rail	High-speed train						X			
Rail	Inner city train						X			
Waterway	Vessel		X				X		X	
Air	Passenger flight (domestic)									X
Air	Passenger flight (intern.)									X
Air	Air freight (domestic)									X
Air	Air freight (intern.)									X

[*] Two variants: conventional BEV and OCST

Table A.18: Assumption for charging infrastructure, numbers represent the probablity of the availability of certain charging option at different locations [9]

Location	**Charging Power**	**2020**	**2030**	**2040**	**2050**
Home	3.7 kW	70 %	50 %	50 %	50 %
	11 kW	30 %	35 %	35 %	35 %
	22 kW	0 %	15 %	15 %	15 %
Work	3.7 kW	10 %	35 %	26 %	34 %
	11 kW	0 %	9 %	13 %	17 %
	22 kW	0 %	9 %	13 %	17 %
Public	3.7 kW	0 %	0 %	26 %	34 %
	11 kW	0 %	0 %	13 %	17 %
	22 kW	5 %	10 %	16 %	22 %

Table A.19: Assumptions for battery capacity in the scenarios [9]

		Battery capacity in kWh			
Segment	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Small car	BEV	29.2	32.4	32.4	32.4
	PHEV	7.4	8.2	8.2	8.2
Compact car	BEV	41.9	46.9	46.9	46.9
	PHEV	8.4	9.4	9.4	9.4
Medium car	BEV	45.9	51.8	51.8	51.8
	PHEV	10.1	11.4	11.5	11.4
Upper class car	BEV	99.2	112.0	112.0	112.0
	PHEV	10.8	12.2	12.2	12.2

Table A.20: CAPEX of vehicle types in passenger road transport based on Conrad et al. [9]

		CAPEX in €			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
Small car	Petrol ICEV	13,979	14,879	15,134	15,186
Small car	Diesel ICEV	16,015	16,748	17,210	17,463
Small car	LPG ICEV	13,979	14,879	15,134	15,186
Small car	CNG ICEV	13,856	14,756	15,011	15,064
Small car	HEV	18,198	17,212	16,833	16,488
Small car	BEV	20,651	16,925	15,193	13,399
Small car	PHEV	20,527	19,295	18,856	18,338
Small car	FCEV	21,515	15,869	14,517	13,093
Compact car	Petrol ICEV	24,318	25,454	25,705	25,866
Compact car	Diesel ICEV	27,906	28,908	29,558	30,022
Compact car	LPG ICEV	24,318	25,454	25,705	25,866
Compact car	CNG ICEV	27,026	28,162	28,413	28,574
Compact car	HEV	29,858	28,719	28,191	27,839
Compact car	BEV	34,282	28,648	26,379	24,041
Compact car	PHEV	33,765	32,375	31,944	31,405
Compact car	FCEV	37,840	29,079	27,009	24,858
Medium car	Petrol ICEV	32,827	33,964	34,215	34,375
Medium car	Diesel ICEV	38,105	39,106	39,756	40,220
Medium car	LPG ICEV	32,827	33,964	34,215	34,375
Medium car	CNG ICEV	35,353	36,489	36,740	36,901
Medium car	HEV	33,175	32,606	31,508	31,156
Medium car	BEV	41,374	35,254	32,725	30,129
Medium car	PHEV	41,175	39,474	38,908	38,237
Medium car	FCEV	47,269	36,797	34,331	31,785
Upper class car	Petrol ICEV	55,150	56,615	56,859	57,032
Upper class car	Diesel ICEV	63,423	65,107	65,388	65,587
Upper class car	LPG ICEV	55,150	56,615	56,859	57,032
Upper class car	CNG ICEV	44,383	45,849	46,093	46,265
Upper class car	HEV	55,931	54,351	53,753	53,291
Upper class car	BEV	74,798	63,021	58,045	52,981
Upper class car	PHEV	69,786	67,969	67,368	66,667
Upper class car	FCEV	66,207	55,194	52,702	50,103
Motorcycle	Petrol ICEV	6,644	6,981	7,076	7,096
Motorcycle	BEV	8,194	7,733	7,296	6,892

Table A.21: CAPEX of vehicle types in road freight and rail traffic based on Conrad et al. [9]

		CAPEX in €			
Transport type	**Vehicle type**	**2020**	**2030**	**2040**	**2050**
LDV	Petrol ICEV	27,250	27,740	28,230	28,720
LDV	Diesel ICEV	27,250	27,740	28,230	28,720
LDV	LPG ICEV	27,250	27,740	28,230	28,720
LDV	CNG ICEV	28,841	28,707	28,573	28,440
LDV	BEV	39,187	36,261	33,336	30,411
LDV	FCEV	68,576	59,119	49,663	40,207
MDV	Petrol ICEV	45,945	50,059	54,173	58,287
MDV	Diesel ICEV	45,945	50,059	54,173	58,287
MDV	LPG ICEV	45,945	50,059	54,173	58,287
MDV	CNG ICEV	66,174	66,878	67,582	68,287
MDV	BEV	105,974	98,026	90,078	82,130
MDV	FCEV	168,331	137,533	106,736	75,939
HDV	Diesel ICEV	70,666	81,998	81,998	81,998
HDV	CNG ICEV	114,333	143,000	143,000	143,000
HDV	BEV	166,470	130,176	130,176	130,176
HDV	FCEV	252,412	121,057	121,057	121,057
Semi-trailer	Diesel ICEV	110,891	128,673	128,673	128,673
Semi-trailer	CNG ICEV	118,985	195,910	195,910	195,910
Semi-trailer	BEV	166,470	185,177	185,177	185,177
Semi-trailer	BEV OCST	196,258	137,916	137,916	137,916
Semi-trailer	FCEV	522,047	174,000	174,000	174,000
Freight train	Diesel ICEV	1,700,000	2,112,500	2,112,500	2,112,500
Freight train	Electric drive	3,275,000	3,275,000	3,275,000	3,275,000
Local train	Diesel ICEV	4,800,000	4,800,000	4,800,000	4,800,000
Local train	Electric drive	3,555,555	3,555,555	3,555,555	3,555,555
Long-distance train	Diesel ICEV	3,275,000	3,275,000	3,275,000	3,275,000
Long-distance train	Electric drive	3,275,000	3,275,000	3,275,000	3,275,000
High-speed train	Electric drive	7,150,000	7,150,000	7,150,000	7,150,000
Inner city train	Electric drive	5,880,000	5,880,000	5,880,000	5,880,000

Table A.22: CAPEX of vehicle types in air and water traffic based on Conrad et al. [9]

Transport type	**Vehicle type**	**CAPEX in €** **2020**	**2030**	**2040**	**2050**
Vessel	Diesel ICEV	2,000,000	2,000,000	2,000,000	2,000,000
Vessel	FCEV	2,700,000	1,890,000	1,890,000	1,890,000
Aircraft (domestic)	Turbine	74,710,224	74,710,224	74,710,224	74,710,224
Aircraft (internat.)	Turbine	213,850,936	213,850,936	213,850,936	213,850,936

Table A.23: CAPEX of vehicle types of buses and coaches based on Conrad et al. [9]

Transport type	**Vehicle type**	**CAPEX in €** **2020**	**2030**	**2040**	**2050**
All buses	Petrol ICEV	230,000	231,100	231,100	231,100
All buses	Diesel ICEV	230,000	231,100	231,100	231,100
All buses	CNG ICEV	256,404	247,180	247,180	247,180
All buses	BEV	535,000	437,610	437,610	437,610
All buses	FCEV	426,000	239,300	239,300	239,300
All coaches	Petrol ICEV	260,000	261,100	261,100	261,100
All coaches	Diesel ICEV	260,000	261,100	261,100	261,100
All coaches	CNG ICEV	289,848	279,267	279,267	279,267
All coaches	BEV	700,000	572,574	572,574	572,574
All coaches	FCEV	487,200	281,300	281,300	281,300

A.3 Scenario Results

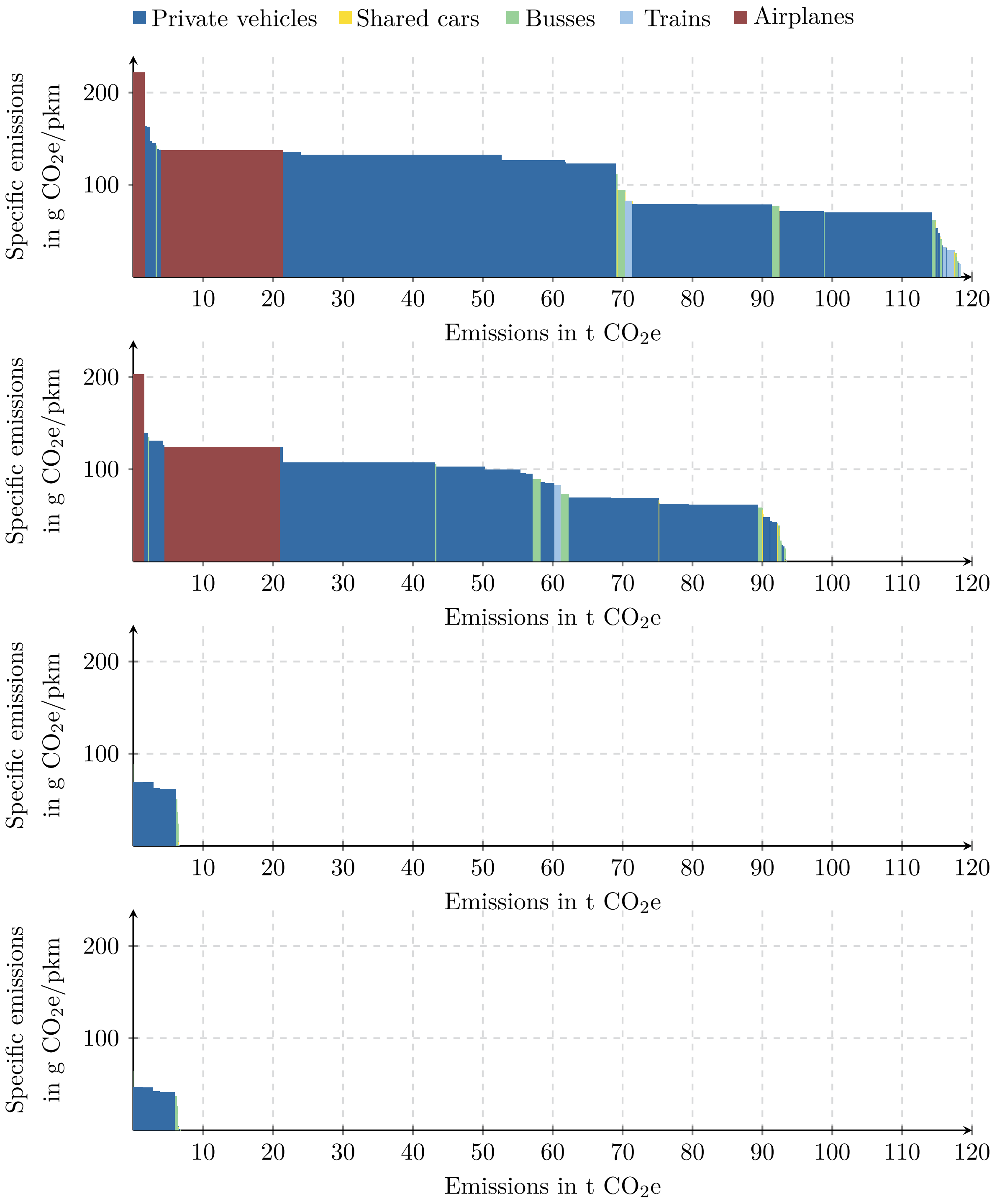

Figure A.1: Emission merit order of vehicle types in passenger transport in the scenario Trend-CoHC from 2020 (top) to 2050 (bottom)

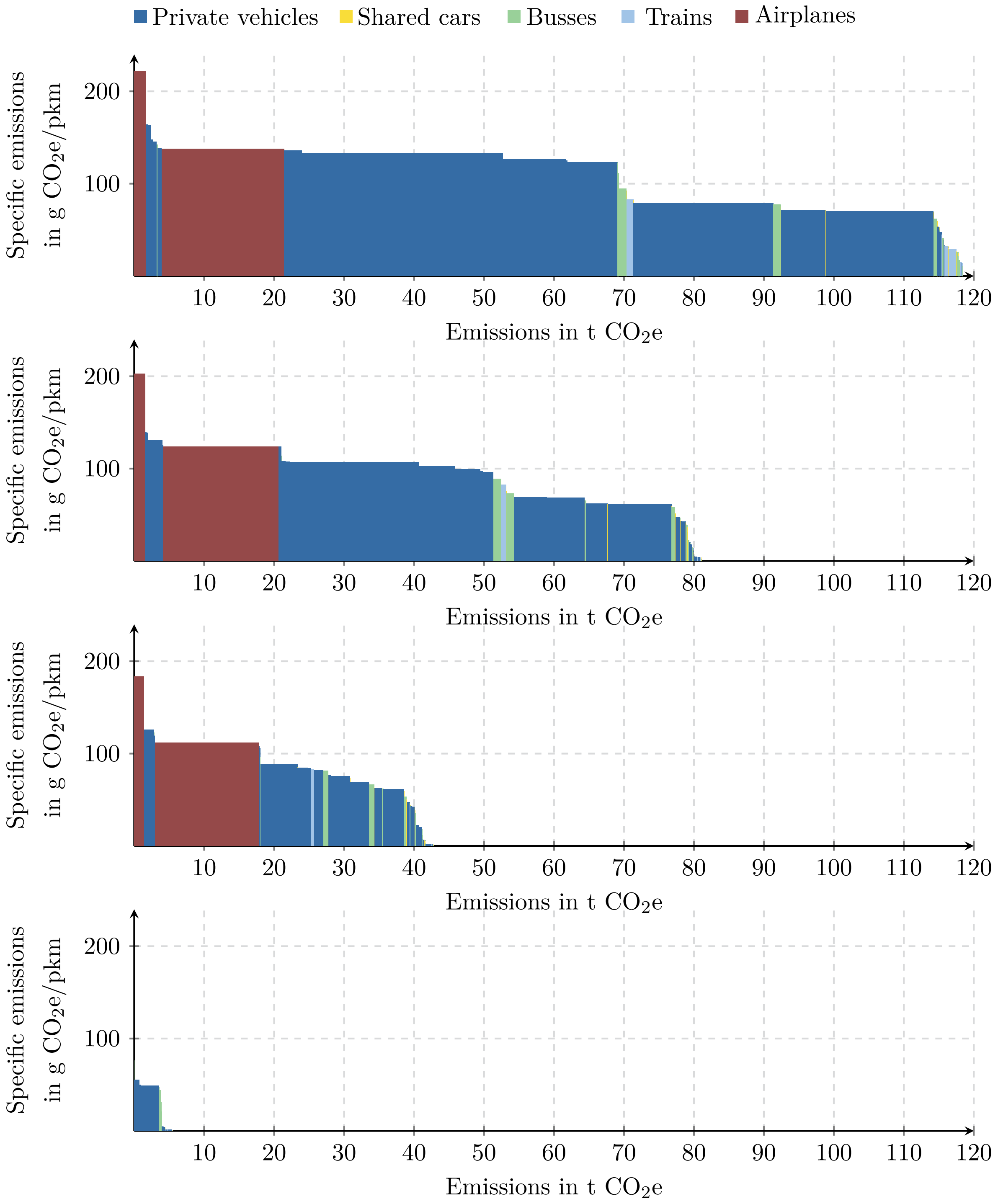

Figure A.2: Emission merit order of vehicle types in passenger transport in the scenario Trend-Elec from 2020 (top) to 2050 (bottom)

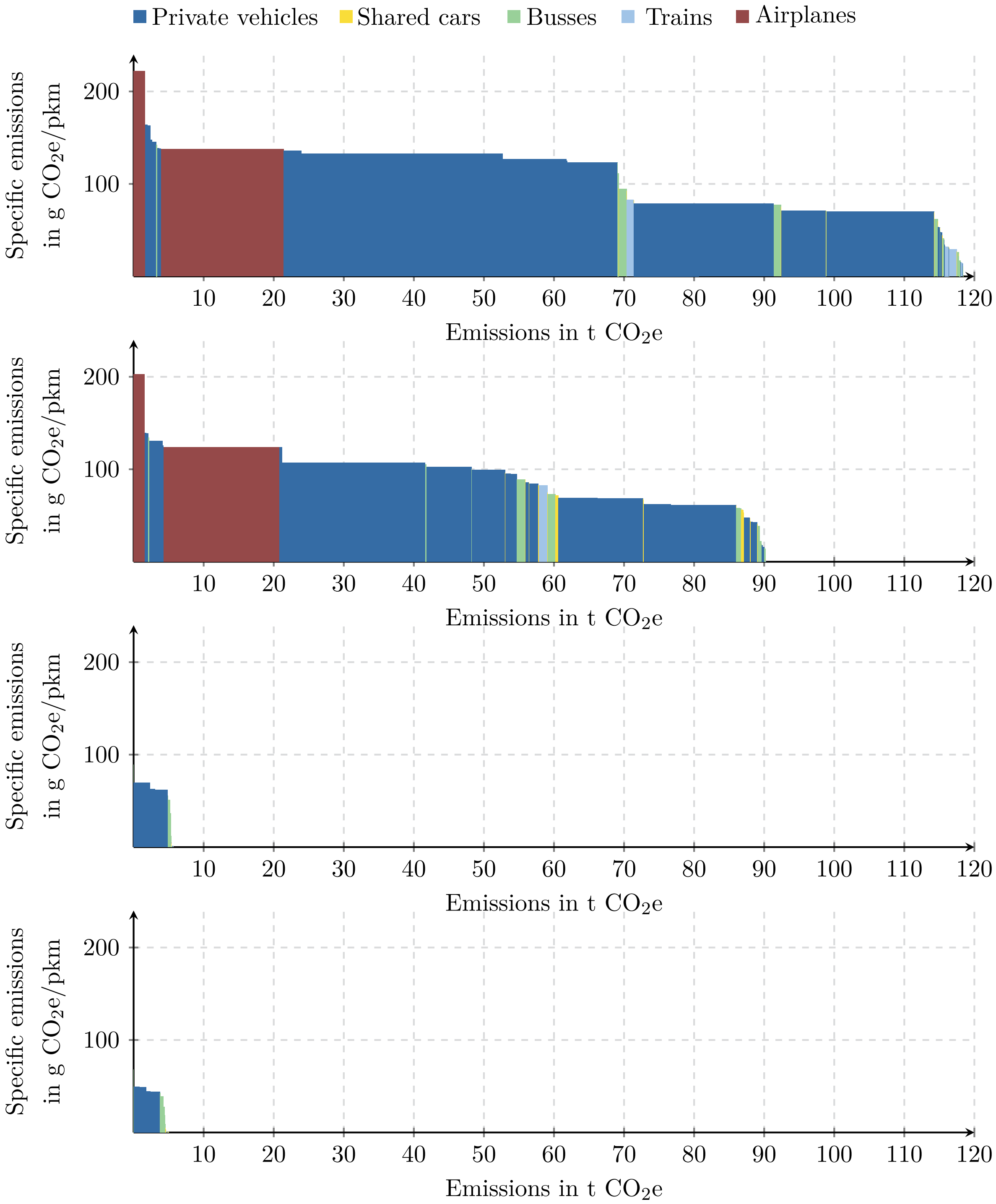

Figure A.3: Emission merit order of vehicle types in passenger transport in the scenario Multi-CoHC from 2020 (top) to 2050 (bottom)

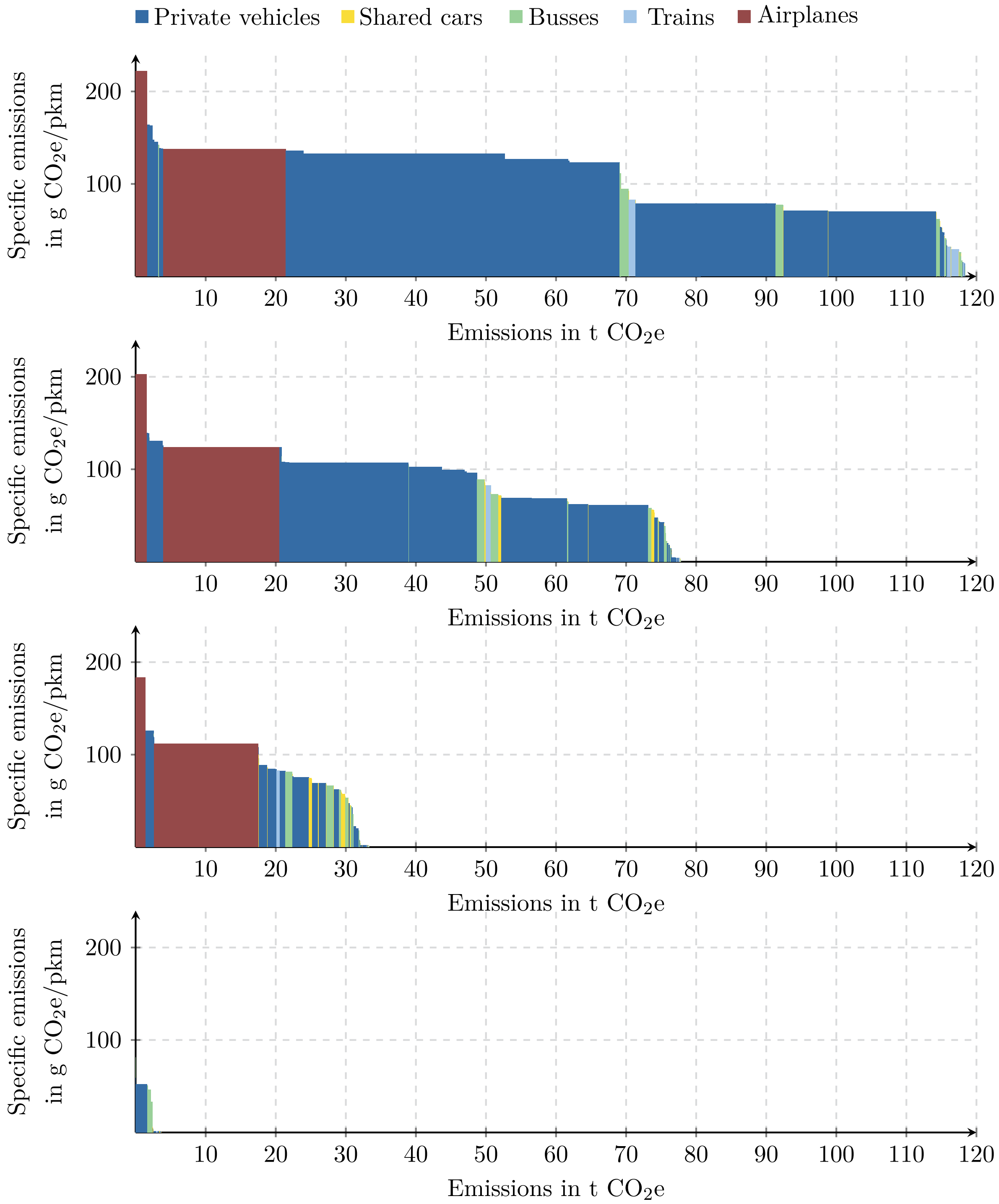

Figure A.4: Emission merit order of vehicle types in passenger transport in the scenario Multi-Elec from 2020 (top) to 2050 (bottom)

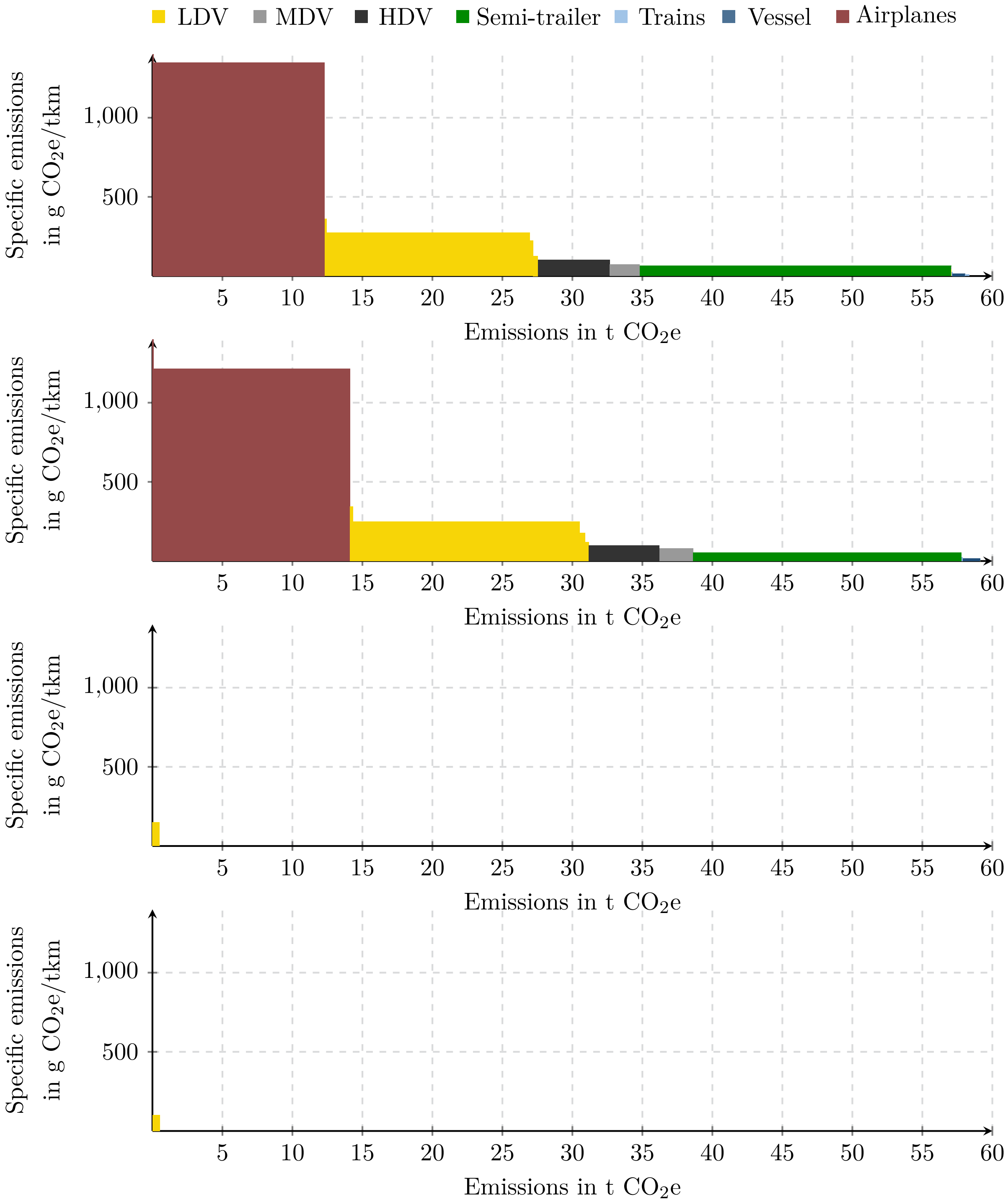

Figure A.5: Emission merit order of vehicle types in freight transport in the scenario Trend-CoHC from 2020 (top) to 2050 (bottom)

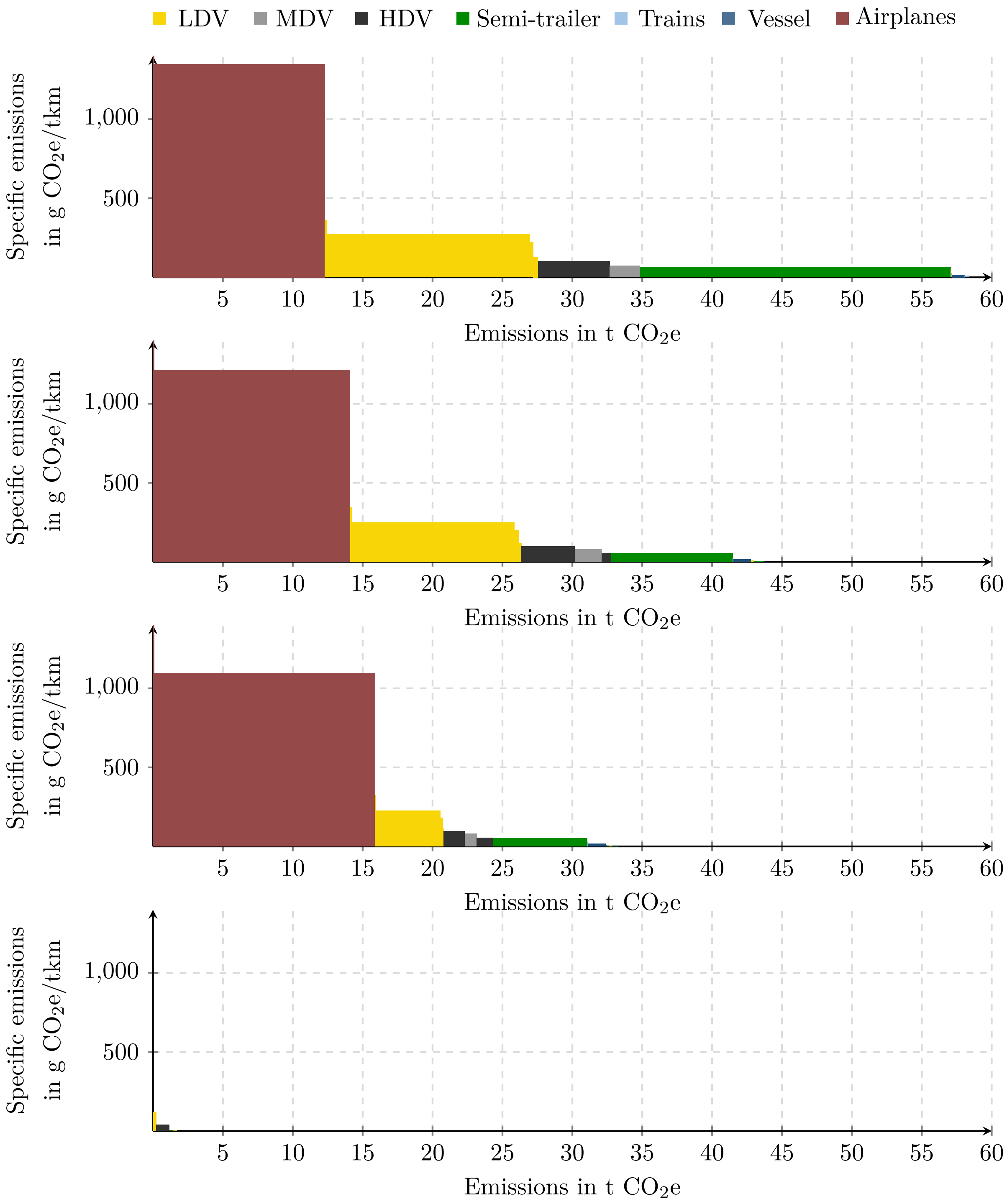

Figure A.6: Emission merit order of vehicle types in freight transport in the scenario Trend-Elec from 2020 (top) to 2050 (bottom)

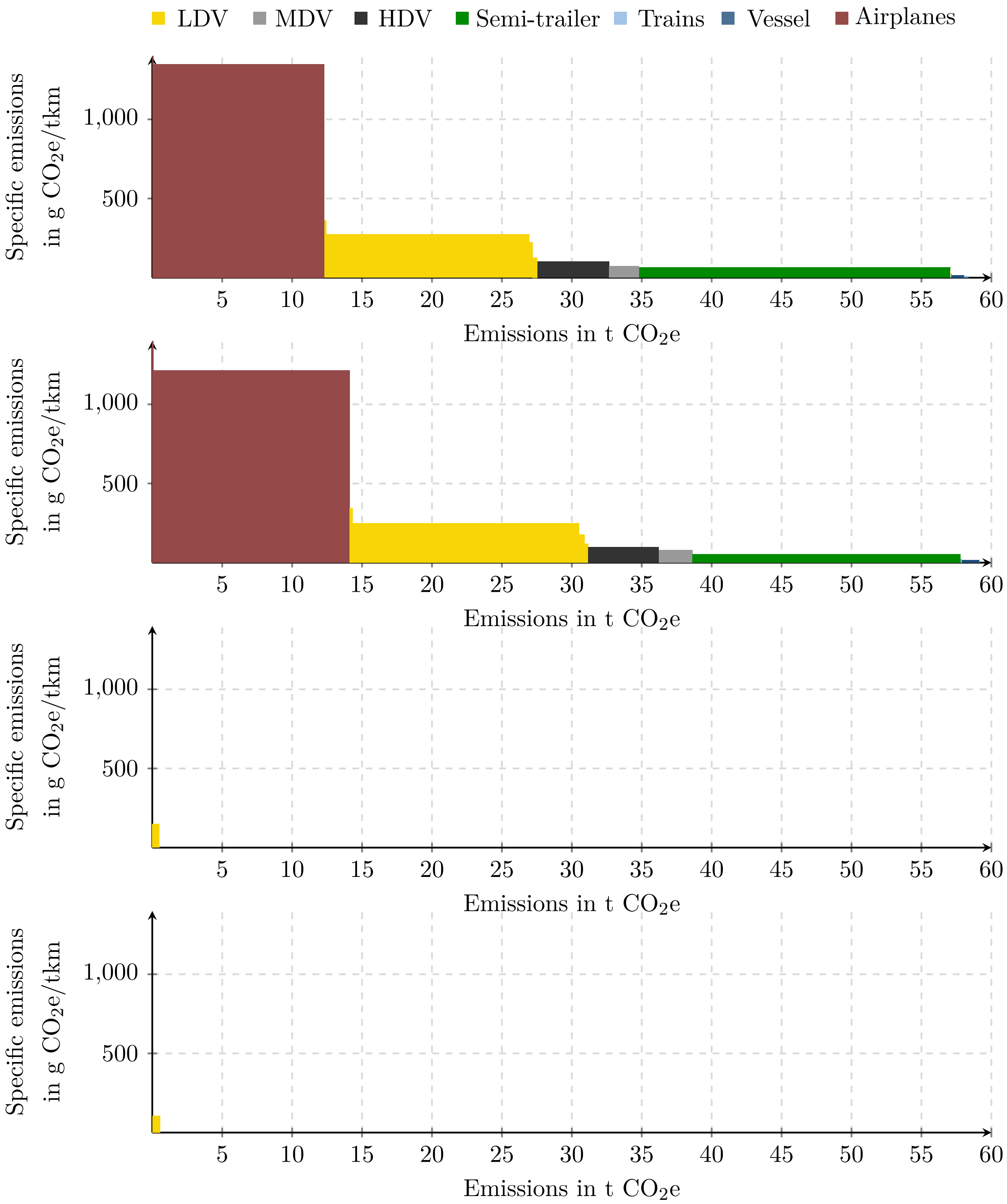

Figure A.7: Emission merit order of vehicle types in freight transport in the scenario Multi-CoHC from 2020 (top) to 2050 (bottom)

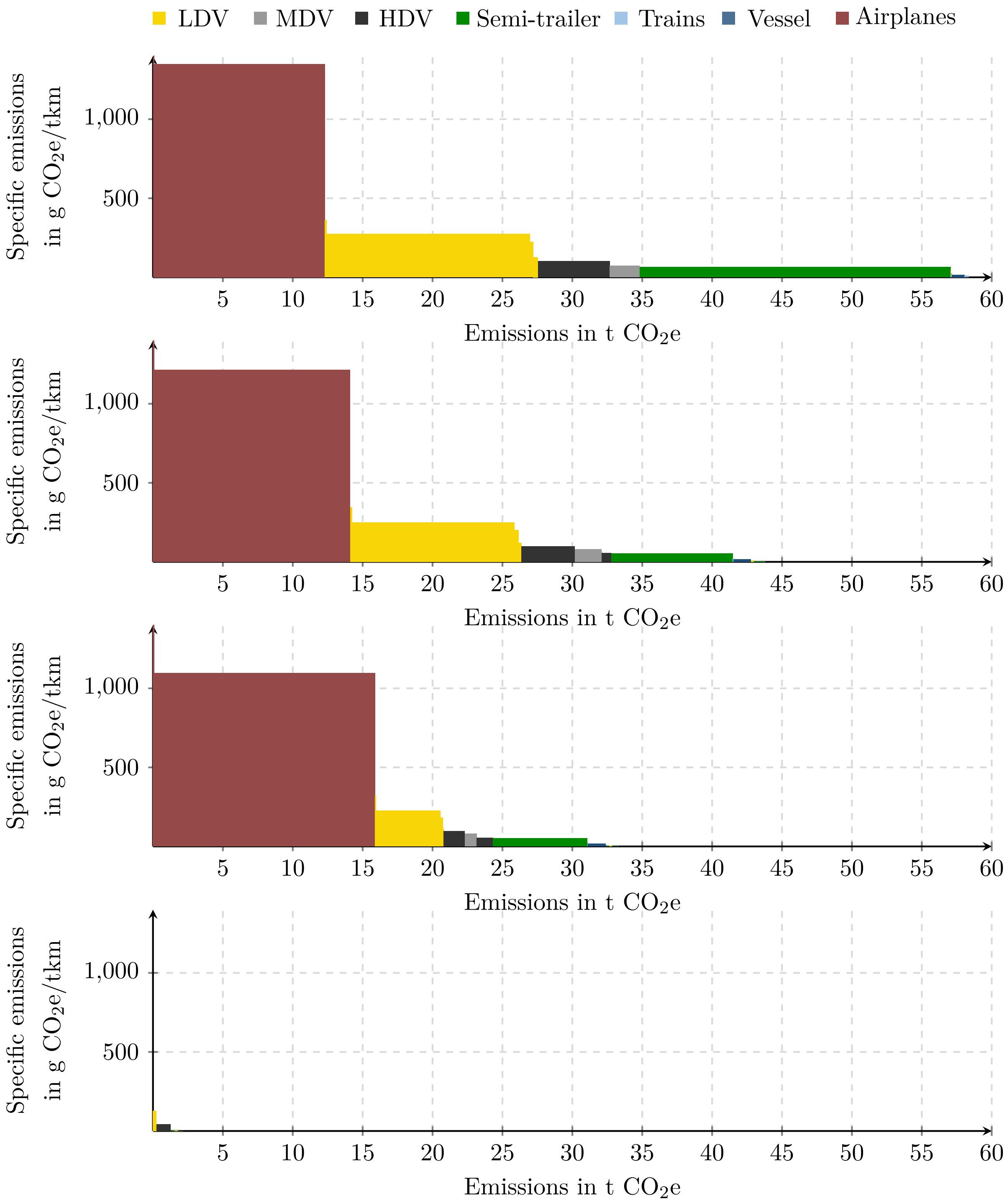

Figure A.8: Emission merit order of vehicle types in freight transport in the scenario Multi-Elec from 2020 (top) to 2050 (bottom)

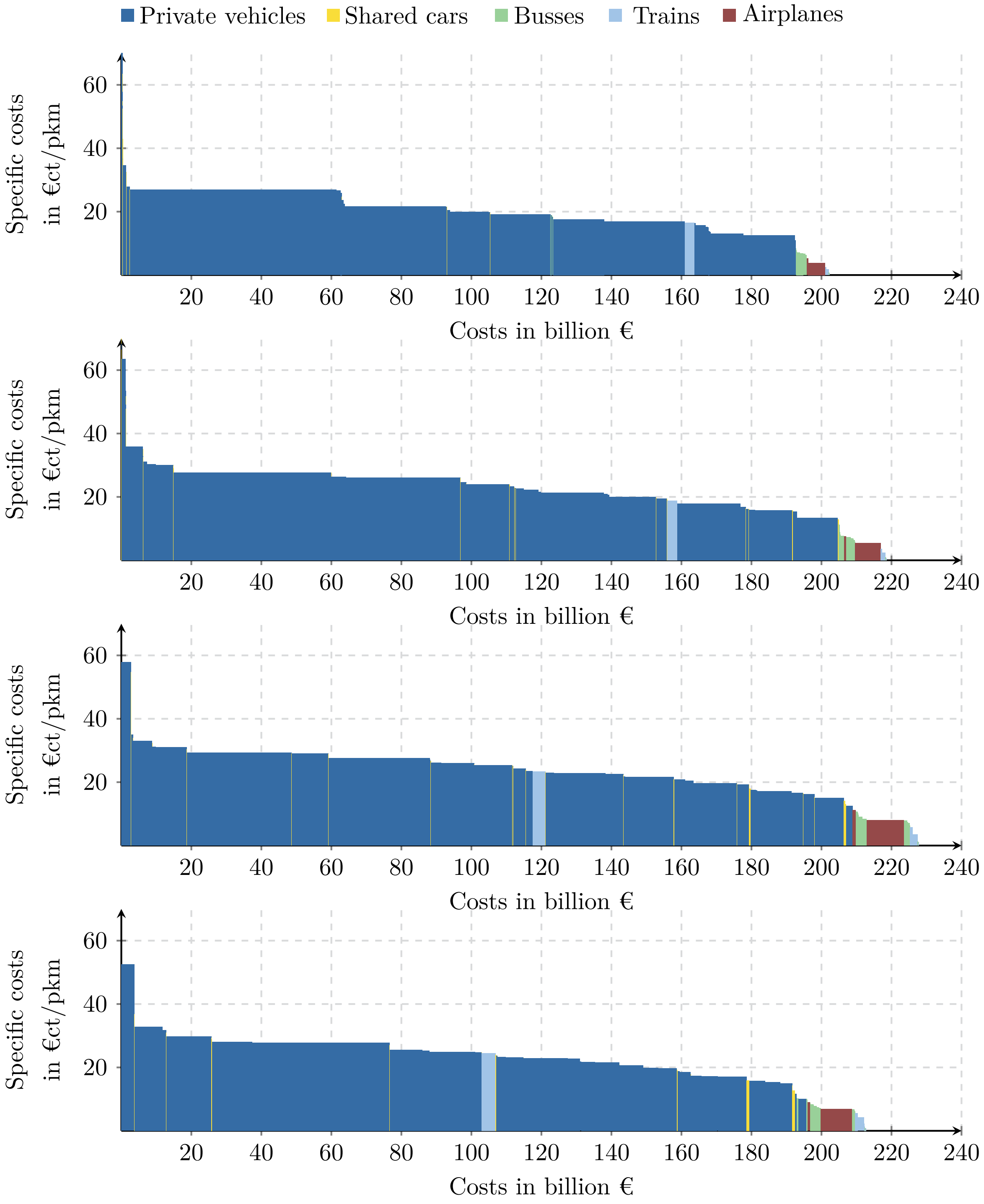

Figure A.9: Cost merit order of vehicle types in passenger transport in the scenario Trend-CoHC from 2020 (top) to 2050 (bottom)

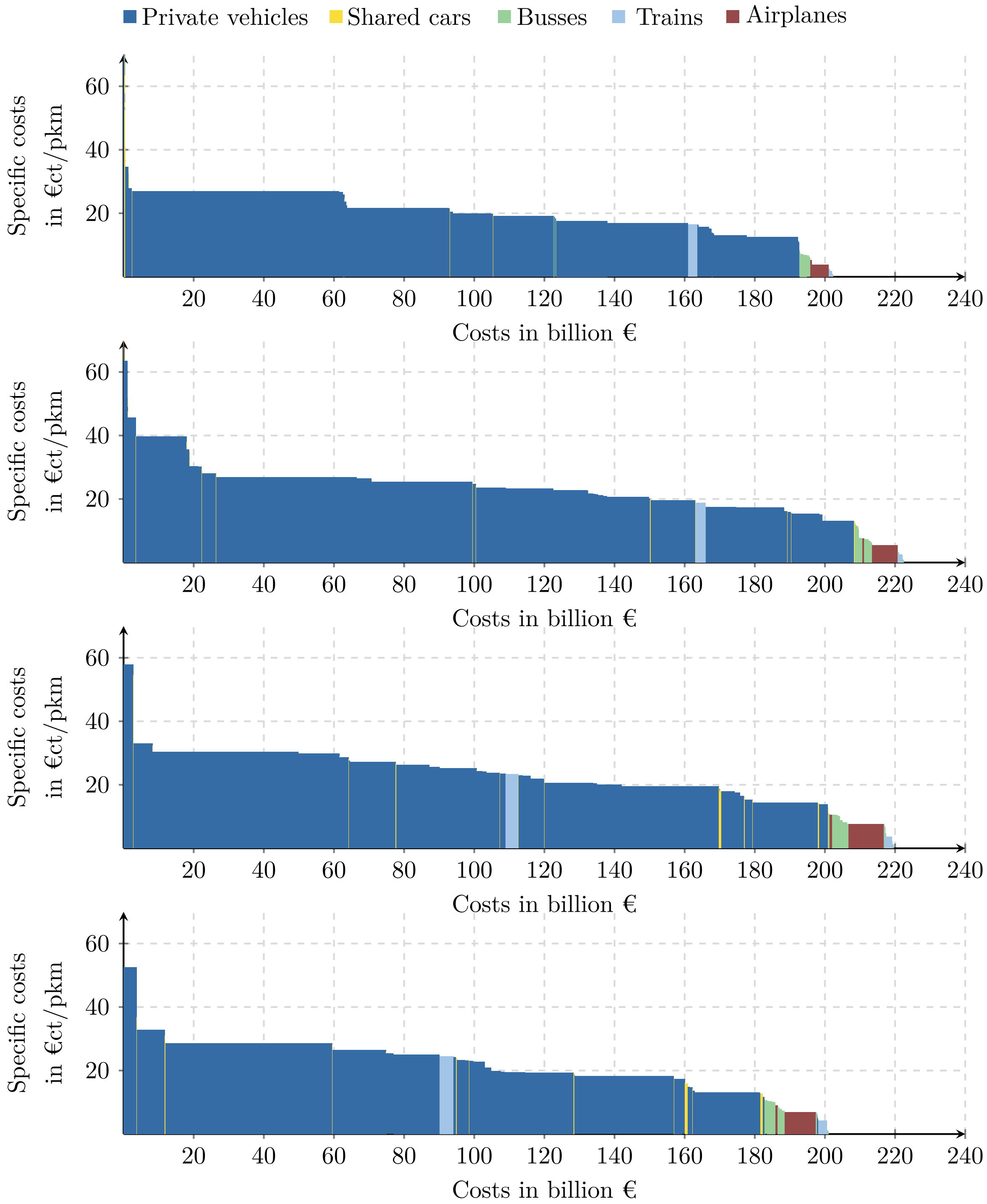

Figure A.10: Cost merit order of vehicle types in passenger transport in the scenario Trend-Elec from 2020 (top) to 2050 (bottom)

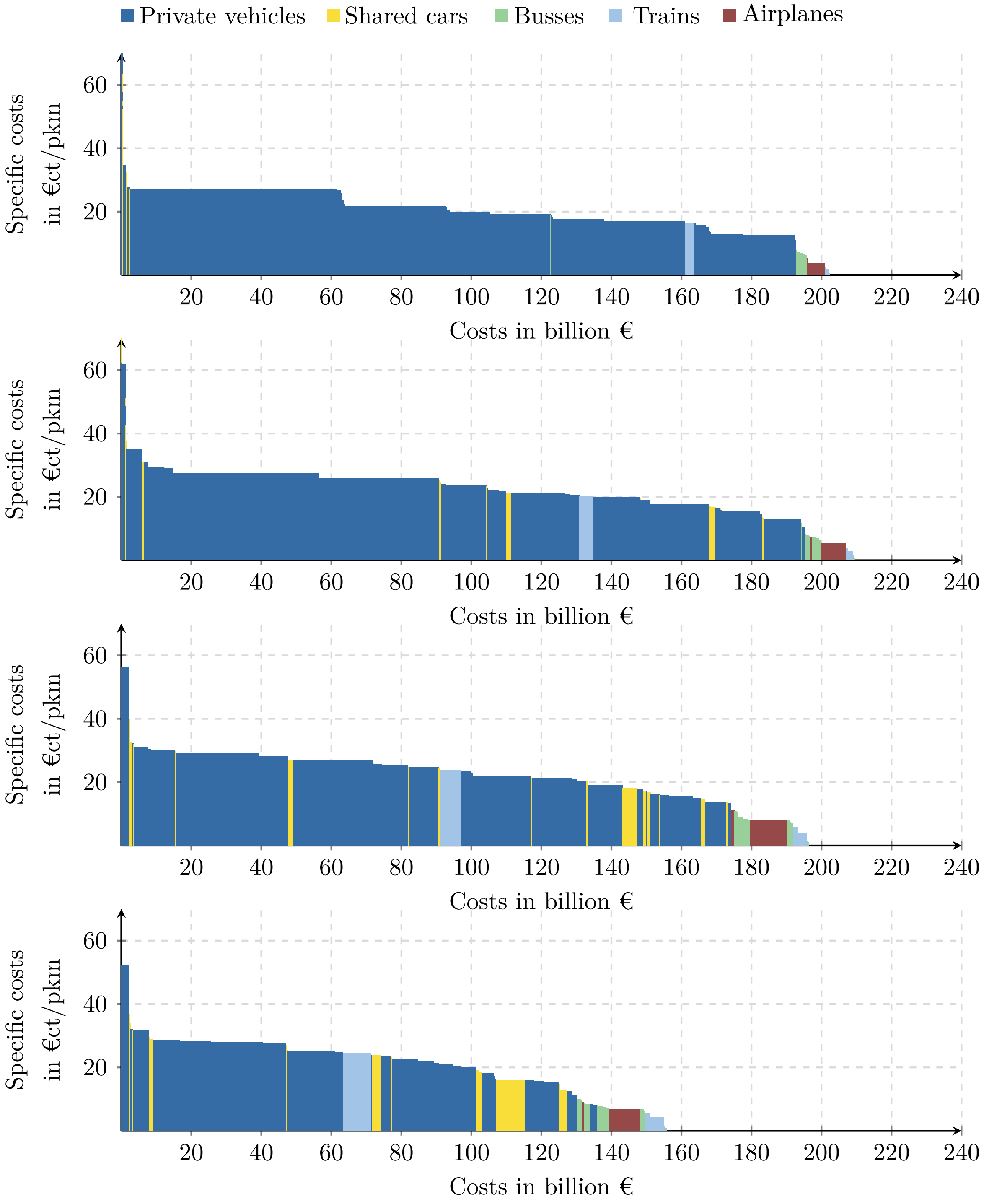

Figure A.11: Cost merit order of vehicle types in passenger transport in the scenario Multi-CoHC from 2020 (top) to 2050 (bottom)

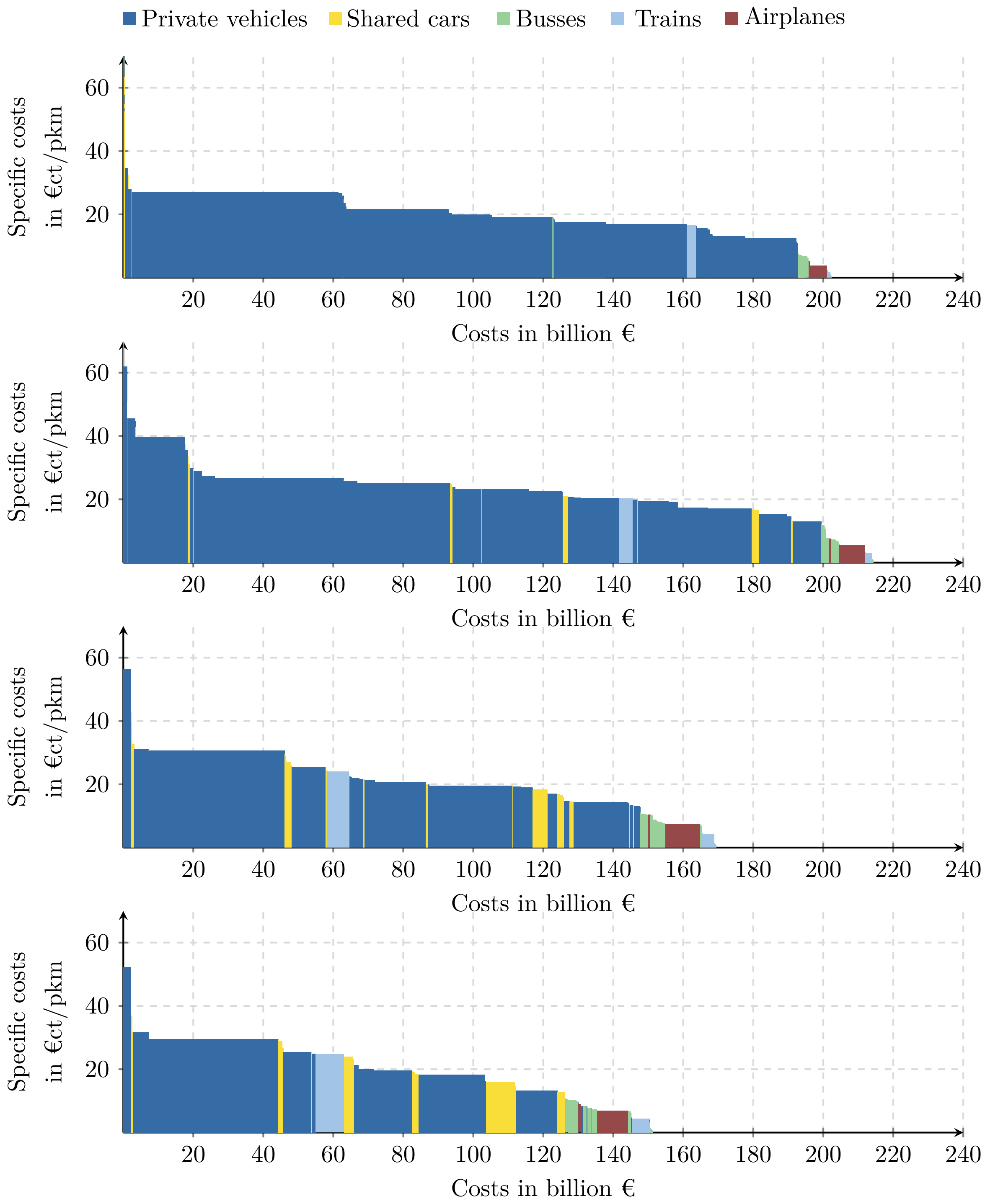

Figure A.12: Cost merit order of vehicle types in passenger transport in the scenario Multi-Elec from 2020 (top) to 2050 (bottom)

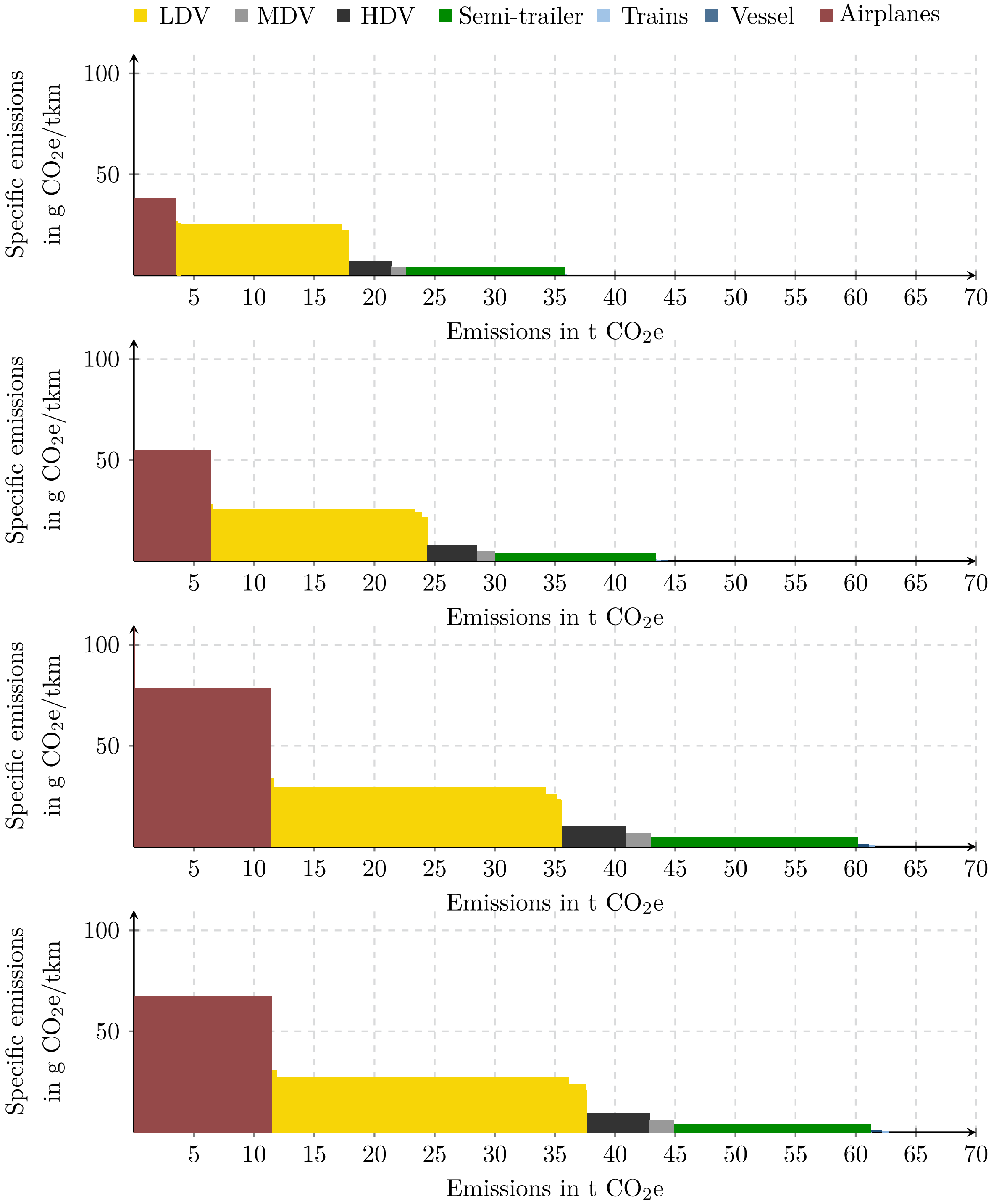

Figure A.13: Cost merit order of vehicle types in freight transport in the scenario Trend-CoHC from 2020 (top) to 2050 (bottom)

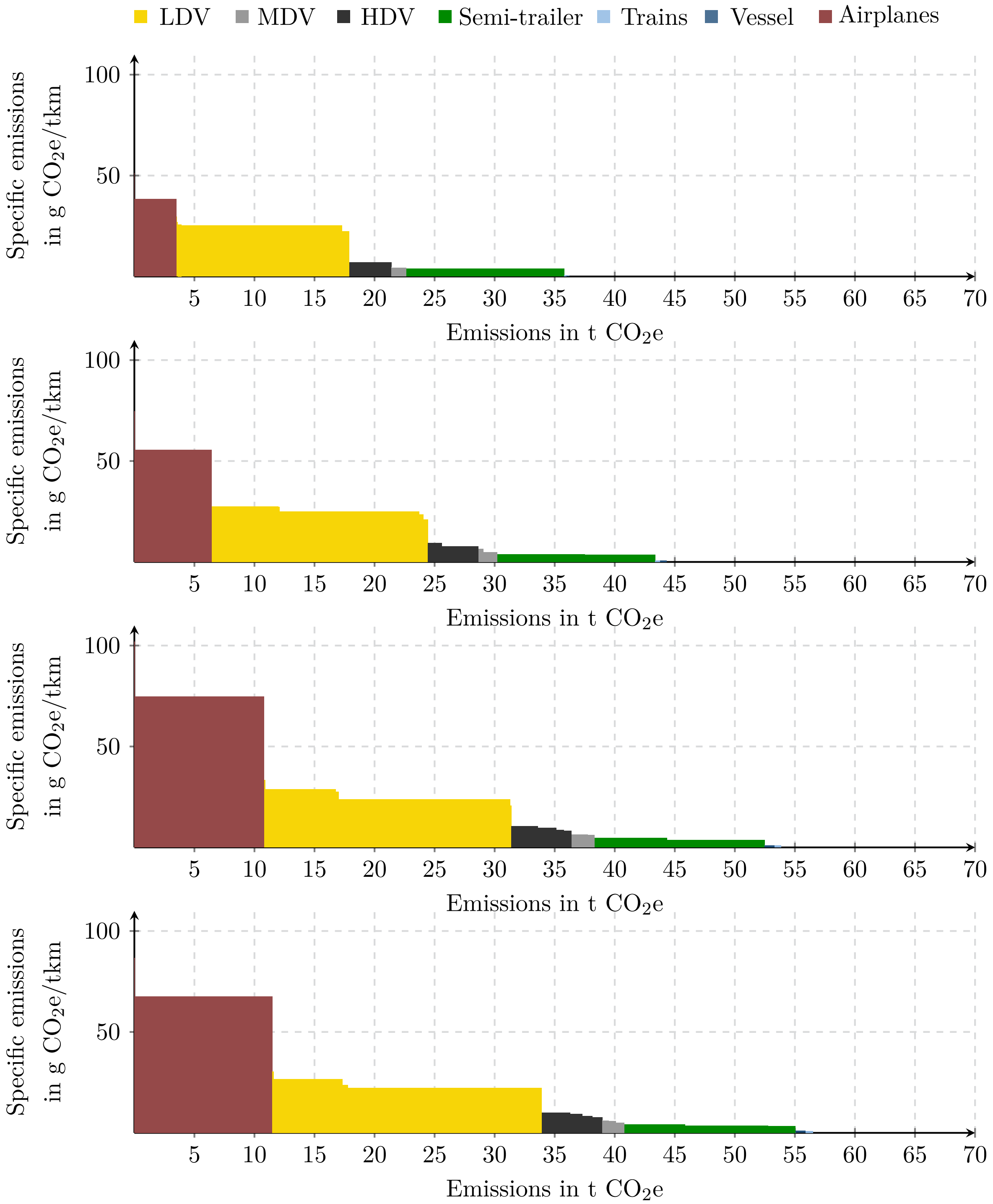

Figure A.14: Cost merit order of vehicle types in freight transport in the scenario Trend-Elec from 2020 (top) to 2050 (bottom)

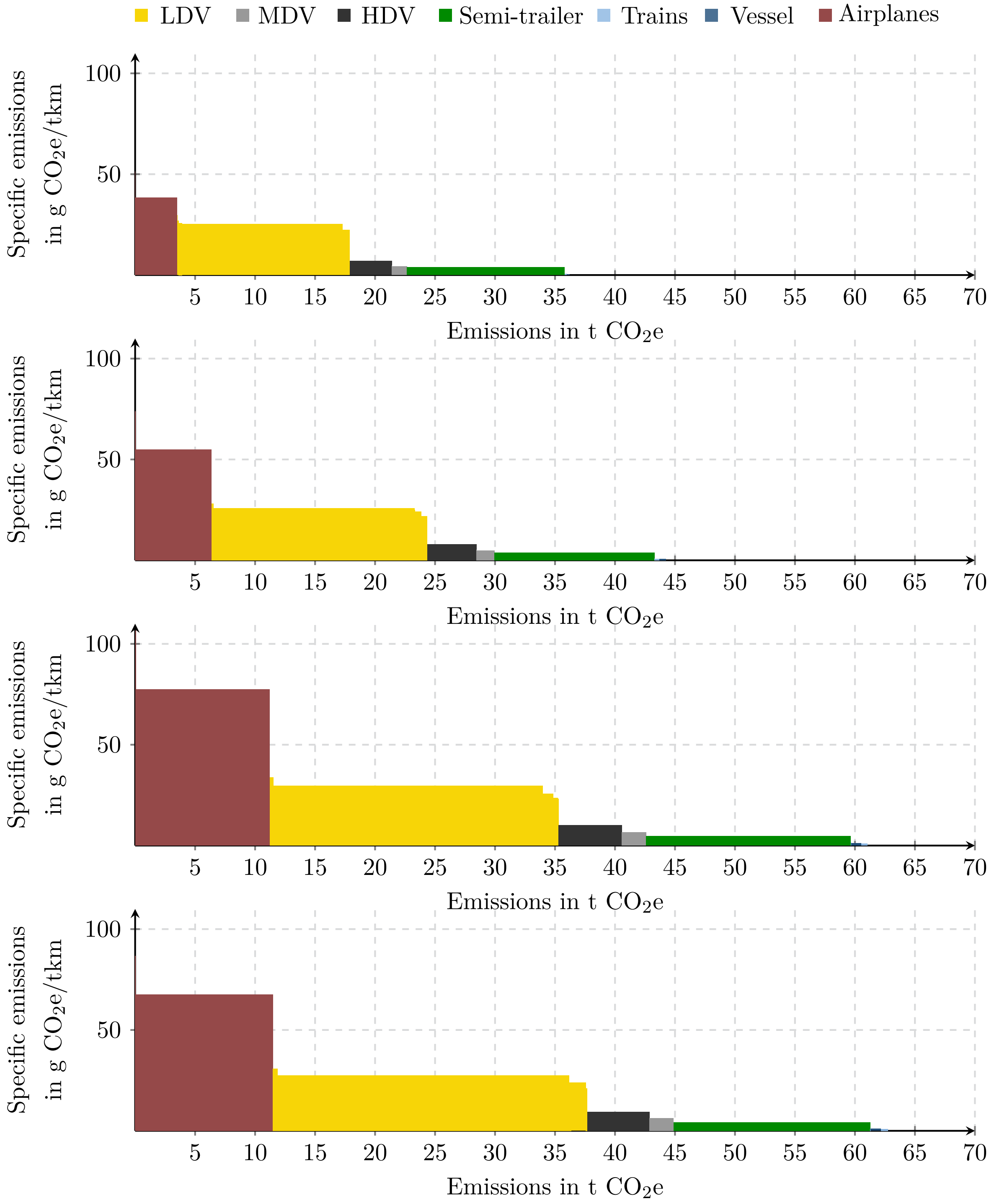

Figure A.15: Cost merit order of vehicle types in freight transport in the scenario Multi-CoHC from 2020 (top) to 2050 (bottom)

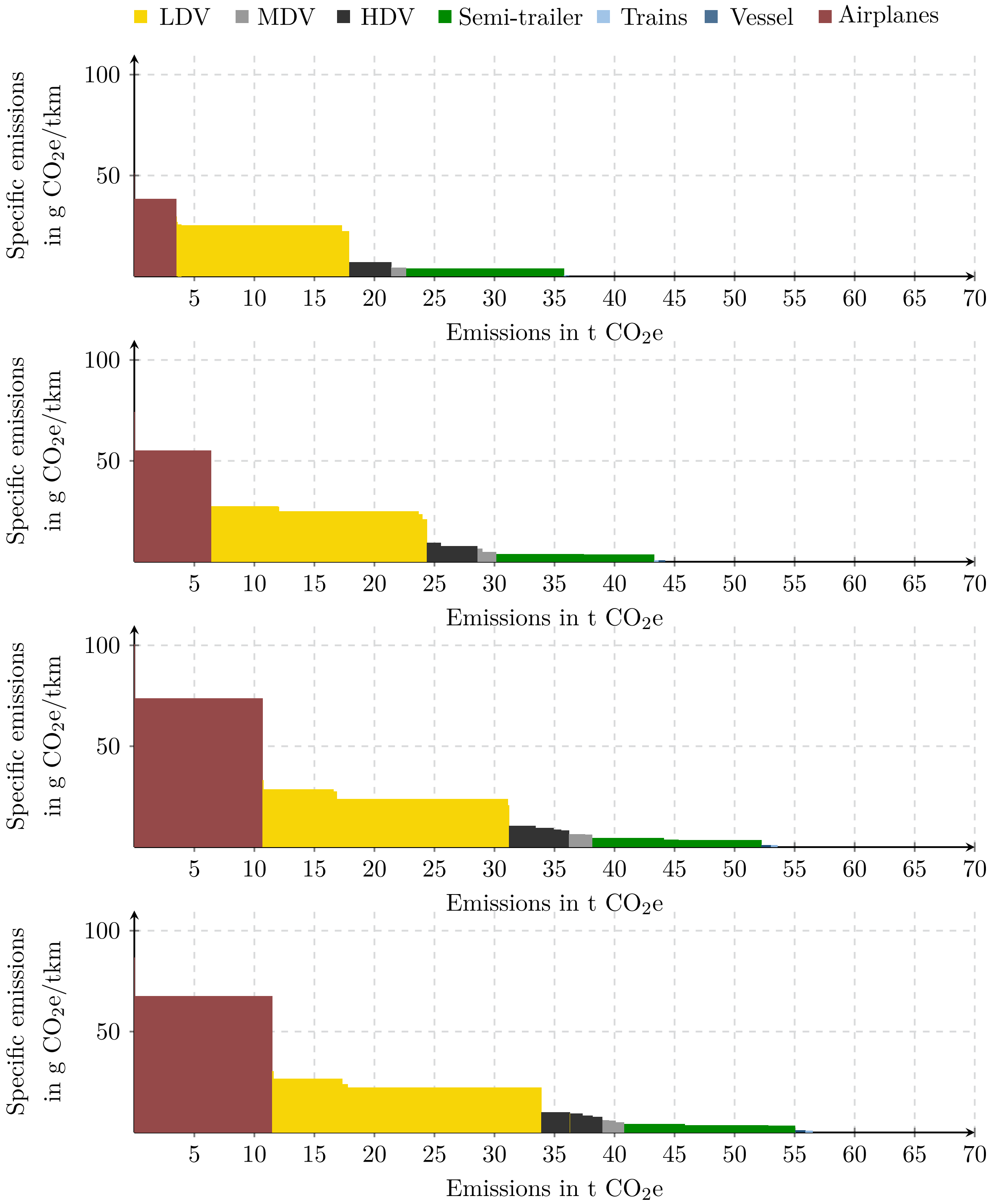

Figure A.16: Cost merit order of vehicle types in freight transport in the scenario Multi-Elec from 2020 (top) to 2050 (bottom)