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“The influence of electrification scenarios in road transport on the climate targets”

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HIGHLIGHTS

- Plausible BEV ramp-up trajectories derived from diffusion models and fleet data.
- Ramp-up differences strongly affect renewable fuel demand and compliance outcomes.
- Fast electrification lowers (renewable) fuel demand and reduces compliance risks.
- Even high BEV shares require renewable fuels to meet interim climate targets.
- Misalignment remains between relative quota frameworks and absolute KSG targets.

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ABSTRACT

The transport sector accounts for about 22% of Germany's greenhouse gas (GHG) emissions and is amongst the most difficult parts of the energy system to decarbonize. The most commonly discussed options for the transport sector are the electrification of drivetrains and the use of renewable fuels. Especially in road transport, the future development depends on millions of individual purchase decisions, which introduces significant uncertainty regarding the speed and extent of electrification. Against this background, this study generates possible ramp-up curves for battery electric vehicles (BEV) using well-established diffusion models, historical vehicle stock data, data for BEV in Germany and literature expectations for future development trends concerning the electrification in road transport. These ramp-up curves are integrated into the vehicle stock in order to investigate the impact of different ramp-ups of BEV on the legal framework and GHG emission reduction obligations in the transport sector. The results show that the energy demand (and its composition) of the sector is strongly influenced by the degree of electrification in road transport. However, even with high shares of BEV in the vehicle stock, a significant use of renewable fuels will be necessary to meet the regulatory framework conditions under the Renewable Energy Directive (RED), the German GHG quota and the German Climate Change Act (KSG) in order to realize both blending quotas and absolute GHG emission reductions according to the German sector targets for transport.

1. Introduction

In recent years, climate protection has increasingly become the focus of legislative efforts. Sector-specific regulations have emerged, targeting sectors such as energy, industry, and transport. The Kyoto Protocol from 1997 [1] and the Paris Agreement from 2015 [2] are globally accepted agreements (the latter has been ratified by 194 countries, including the European Union (EU)), which, however, only specify greenhouse gas (GHG) reduction goals, but neither set precise targets nor specify how to achieve them [3]. Based on this overarching legal framework, on a supranational and national level, more detailed legal requirements are already in place. One example, the “Green Deal” of the European Union, aims at achieving “net-zero” GHG emissions for all member states until 2050 [4]. “Net-zero” means in this case that remaining GHG emissions from fossil fuels are balanced by “sinks”, reducing the amount of atmospheric carbon dioxide (CO_2) or other GHG equally [5]. EU member states can also set more ambitious targets, as, e.g., Germany aiming at “net-zero” until 2045 [6,7].

As a result, fossil fuel-based systems are gradually being transformed into these “net-zero” systems. For some sectors, possible transition

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pathways to reduce their GHG emissions are relatively well defined; one example is the strong expansion of the use of renewable sources of energy for electricity provision within the energy sector (e.g., photovoltaic systems (PV), onshore and offshore wind mills). This is not necessarily true for other sectors of our overall industrialized society; for example, the transport sector continues to face challenges in achieving its climate targets, with GHG emissions remaining relatively stable throughout the past decades [8]; i. e., the transport sector contributes with 31% to the EU-wide GHG emissions in 2024 [8,9].

Against this background, the debate around the most appropriate defossilisation pathway within the transport sector remains contentious. While many stakeholders advocate for the electrification of drivetrains, others emphasize (in addition) the potential role of renewable ("green") fuels, especially for applications difficult to electrify (e.g., aviation, maritime transport, heavy-duty trucks) [10–12,13,14,15]. This debate is mirrored in regulatory discussions – particularly in the context of fleet emission limits for vehicle manufacturers (OEM) – where positions range from claiming a general ban on vehicles with internal combustion engines (ICEVs) to promoting a "technology-neutral" approach by restricting fossil fuel-based GHG emissions rather than specific technologies. Additionally, the Renewable Energy Directive (RED), ReFuelEU Aviation (RAV) and FuelEU Maritime (FEMA) impose obligations on fuel suppliers, including GHG reduction targets and blending quotas for renewable fuels.

Although renewable fuels are already in use, their availability remains limited so far. Meanwhile, the market uptake of battery electric vehicles (BEV) has increased, both within the passenger and commercial transport sectors. Due to their higher efficiency compared to ICEVs, BEV have the potential to substantially reduce energy demand, especially within the ground-based transport sector [16,17]. Nevertheless, this transition and especially the respective market ramp-up depend on the build-up and easily available charging infrastructure as well as the gradual turnover of the current ICEV-dominated vehicle fleet, being especially demanding for utility vehicles [18,19]. As neither option can be used as a standalone solution, a mixture is to be expected – however, this mixture is very much influenced by the aforementioned.

Hence, large-scale energy system models have been used to project possible transformation pathways for regions (e.g., the EU) or specific countries. For example for Germany, respective studies [20–25] apply a variety of modelling approaches to determine drivetrain fleet compositions compatible with exogenously set climate targets and limitations as, e.g., the maximum number of annually possible new registrations of a certain drivetrain as well as the availability of renewable fuels or limitations due to expected developments in purchasing power. These models often propose selected policy bundles based on the outcomes of such a top-down scenario analysis.

Other studies rather focus in detail on the BEV ramp-up, using, e.g., stock models or agent-based models to simulate consumer adoption under varying assumptions [26,27]. Other investigations focus on scenario-based approaches, where favourable conditions supporting or promoting certain technologies are examined to further understand the underlying system dynamics [22]. However, these modelling approaches are typically data- and computation-intensive, limiting typically the number of scenarios that can be feasibly explored. In addition, they require detailed input on technology costs, on infrastructure, on behavioural aspects, and on system interactions – information that is often uncertain, not readily available, and/or characterized by strong short-term fluctuations.

Another option for the modelling of fleet developments is the use of diffusion models [28–32]. Such diffusion models are often used to imitate the rollout of new technologies into an already existing market.

Diffusion models originally evolved from applications in biological growth and demography, such as describing cell or population growth, and were subsequently transferred to an inderdisciplinary use, e.g., diffusion of innovative products and technology adoption processes [29,33]. Today, they are widely used to describe and analyse the temporal adoption of innovations and technologies across different domains [26–35].

The models are based on the empirical observation that many technological, economic, and social processes follow a sigmoidal ("S-shaped") growth trajectory [26–28,33]. Such a model typically captures an initial phase of slow adoption, followed by accelerated growth, and eventually a saturation phase as market potential becomes exhausted or external constraints limit further expansion [27,28,32,33]. Thereby, the ramp-up of new technologies can exhibit varying shapes and dynamics, depending on technological maturity, policy incentives, consumer behaviour, and infrastructure readiness [27,32,33].

Over time, classical diffusion models have been extended in various ways to account more explicitly for external influences, such as policy interventions, price developments or technology-specific factors [32]. These extensions typically rely on additional explanatory variables, time-varying parameters, or hybrid modelling approaches, thereby increasing both data requirements and the number of underlying assumptions [28,31,33].

While such approaches may improve behavioural realism under well-specified conditions, they require detailed and consistent input data over time and are sensitive to assumptions regarding future developments. [27,31,33] Consequently, various (i.e., also those without additional input) diffusion models remain widely applied, particularly in the analysis of emerging technologies or long-term scenarios in which key market parameters – such as long-term market potential or adoption dynamics – are subject to substantial uncertainty or cannot be robustly specified ex ante. [31–34].

However, parsimonious diffusion models are employed in this study to represent alternative BEV ramp-up pathways under uncertain long-term conditions. Given the limited availability of robust input data for future policy instruments and market dynamics, a simplified diffusion-based approach enables a transparent and scenario-consistent analysis of fleet development. To account for heterogeneity in possible diffusion patterns, the logistic function (LF), the Gompertz model (GM), and the Bass diffusion model (BDM) are selected, as each captures a distinct type of market roll-out and has been applied in comparable contexts [26–28,31–33,35]

- The logistic function (LF) assumes that the growth rate at any point in time is proportional to both the existing level of adoption and the remaining growth potential [28]. Due to this characteristic, it is well-suited for modelling bounded growth phenomena in diverse domains such as technology adoption, energy transitions, and behaviour of consumers [28]. The logistic function follows a symmetric shape; i.e., the maximum adoption rate is reached after 50% of the market potential [28,33].
- Beyond the basic logistic model, a variety of other S-shaped functions have been proposed to account for different empirical patterns [28,32,33]. An often used model is the Gompertz model (GM), as it is asymmetric and characterized by early rapid growth that gradually decelerates, making it suitable for systems where early adopters dominate and saturation is approached slowly [28,32].
- In contrast, the Bass diffusion model (BDM) explicitly incorporates two behavioural mechanisms: innovation (external influence) and imitation (internal influence) [26,34,36]. The Bass model distinguishes between "innovators," who adopt a technology independently of others, e.g., on the basis of the influence of policies or marketing, and "imitators," whose adoption is influenced by prior adopters, e.g., by social diffusion mechanisms as word-of-mouth [31,32,34]. It has been widely applied to forecast market dynamics in the absence of extensive historical data [31,32,34]. The Bass diffusion model can be shaped symmetrical or asymmetrical, depending on the growth parameters for innovators and imitators.

Against this background, this study aims to investigate different BEV ramp-up scenarios for Germany and the corresponding interaction with the evolving regulatory framework in terms of GHG emission reduction obligations within the transport sector. Particularly, the frameworks of the RED, ReFuelEU Aviation, FuelEU Maritime, and the German national Climate Change Act are investigated. To this end, a simplified market diffusion model is employed to simulate the development of the vehicle fleet under various assumptions. Based on a variety of published expectations, possible future developments of the German road transport sector are built and analysed, allowing for a broad exploration of regulatory and technological developments within the German transport sector.

2. Legal framework

The legal framework can be divided into the European overarching legislation (EU framework specification) and the specific national legislation in Germany being a member state (MS) of the EU, which declared climate protection goals surpassing the EU targets.

2.1. European legal framework

2.1.1. European green deal. For the EU, a broad variety of regulations addressing environmental policies or supporting certain environmental targets is in place. The overarching framework is the so-called European Green Deal (EGD), first introduced in 2019 [4], which aims at achieving net-zero GHG emissions in the EU by, amongst others, reducing the GHG emissions within the transport sector by 90% until 2050 (against the reference year 1990). By 2030, $30 \cdot 10^6$ zero-emission vehicles and 80,000 zero-emission trucks shall be introduced into the European market. Furthermore, the EU aims to achieve a GHG emission reduction of 55% across all sectors in 2030 against the year of reference 1990.

2.1.2. Fit for 55. The policy package “Fit for 55”, published July 14th, 2021, introduces supporting measures and policies to achieve the target of −55% GHG emissions in 2030 set out by the EGD [37]. Amongst others, it introduces the Emission Trading System II (ETS II), extending the ETS to the road transport sector and the building sector (both aspects are not covered by the ETS I) [38,39]. The package also includes, amongst others, proposals for a new design of the Energy Taxation Directive (ETD) introducing environmental aspects into taxation of energy or the Effort Sharing Regulation (ESR) addressing the GHG emission reductions in sectors not included in the ETS [40,41,42]). Additionally, FuelEU Maritime was introduced, which aims at reducing the GHG emission intensity in maritime transport by a variety of measures (e.g., efficiency improvements, using port-side electricity in harbours, the usage of alternative and/or renewable fuels) [43]. However, there are legal frameworks with a more direct impact on the development of the transport sector, as, e.g., the CO_2 performance standards, ReFuelEU Aviation and the revision of the Renewable Energy Directive [44,45].

2.1.3. CO_2 performance standards. The CO_2 emission performance standards limit the average tailpipe CO_2 emissions that Original Equipment Manufacturers (OEM; vehicle manufacturers) are allowed to have over all vehicles sold. The performance standards for cars and vans gradually decrease up to −100% of the tailpipe GHG emissions against the reference of 2019 in 2035 [46,47]. For heavy-duty vehicles, the performance standard is lowered to −90% of tailpipe GHG emissions in 2040 [5,48]. As a consequence, these performance standards influence the share of zero-emission vehicles (ZEV, e.g., BEV or fuel cell electric vehicles (FCEV)) at new registrations. However, exceptions are already included; in contrast to the methodology of only balancing the tailpipe GHG emissions, so-called “E-Fuels-only” vehicles are discussed, meaning vehicles that are only allowed to use renewable fuels of non-biological origin (RFNBO) as their fuel.

2.1.4. Renewable energy directive. For the transport sector, one of the most relevant regulations is the Renewable Energy Directive (RED), first introduced in 2009 and recast in 2018 (RED II)[49,50]. The latest version of the RED was published on October 31st, 2023 (2023/2413, RED III)[44]. The RED obliges EU member states to achieve one of two overarching goals for 2030: a 14.5% GHG reduction-quota (GHG quota) against a defined fossil reference, using a Well-to-Wake (WtW) approach for the considered GHG emissions, or a share of renewable energies within the total final energy consumption of the transport sector of 29% without considering specific GHG emissions of the energy used. The RED III regulates the entire transport sector, while its predecessor, RED II (2018/2001), only focused on road and rail transport, excluding the maritime and aviation sub-sectors. Amongst other options, a member state can use renewable fuels and energy carriers (e.g., biofuels, hydrogen) or renewable electricity to achieve those goals. Besides the overarching goal, the RED III gives mandatory sub-quotas and limits for the use of different fuel options, differentiated by the origin of the specific option. The different fuel options and the respective limits or sub-quotas are given in Table 1. The RED III states the mandatory targets for each member state; i.e., each MS must adapt the RED into national law and propose pathways to reach those targets until mid of 2025 [44].

2.1.5. ReFuelEU aviation. In addition to the RED III, ReFuelEU Aviation (RAV) is another regulatory framework at the EU level targeting specifically the aviation sector (Fig. 1a) [45]. Here, a minimum share for sustainable aviation fuels (SAF) at the total kerosene consumption is given, both from feedstocks listed in RED III Annex IX and in the form of RNFBO. The quota increases from 2% in 2025 to 70% in 2050 (35% RFNBO)[45]. ReFuelEU Aviation addresses fuel distributors to meet the blending quotas.

2.1.6. FuelEU maritime. Another regulation is FuelEU Maritime (FEMA) addressing maritime transport. Instead of a blending quota for renewable fuels like ReFuelEU Aviation, FEMA uses reduction targets for the GHG intensity of vessels (Fig. 1b) [43]. Until 2050, the GHG intensity must be reduced by 80%. For this purpose, a variety of options can be used (i.e., alternative fuels (not only but also renewable fuels), efficiency measures). Additionally, using onshore electricity can also be counted towards the target. Carbon-capture-and-storage (CCS) of waste gases is also discussed, but not yet introduced as a viable option [43]. However, for maritime transport into or out of the EU, only half of the transport

Table 1
Overview of various options for the RED III as well as limits, mandatory sub-quotas and corresponding multipliers for the year 2030. (RFNBO – Renewable Fuels Of Non-Biological Origin (including hydrogen and derivatives) [44]

Fuel option	Limit	Sub-quota	Multiplicator[1]
Biofuels			
from food and feed crops [2]	7.0		1.0
from feedstock listed in Annex IX part A [3]		5.5	2.0
used in maritime sector			2.4
used in aviation sector			2.4
from feedstock listed in Annex IX part B			2.0
RFNBO [3]		1.0	2.0
used in maritime sector			3.0
used in aviation sector			3.0
Renewable electricity			
used in road sector			4.0
used in rail sector			1.5

[1] Only applicable for the sub-quota and the share of renewable energies.

[2] MS cannot exceed the share used in 2020.

[3] Sub-quota is a combined quota for RFNBO and advanced biofuels of 5.5% in total; RFNBOs must contribute at least 1% to the quota, but can also be used solely to fulfil the quota.

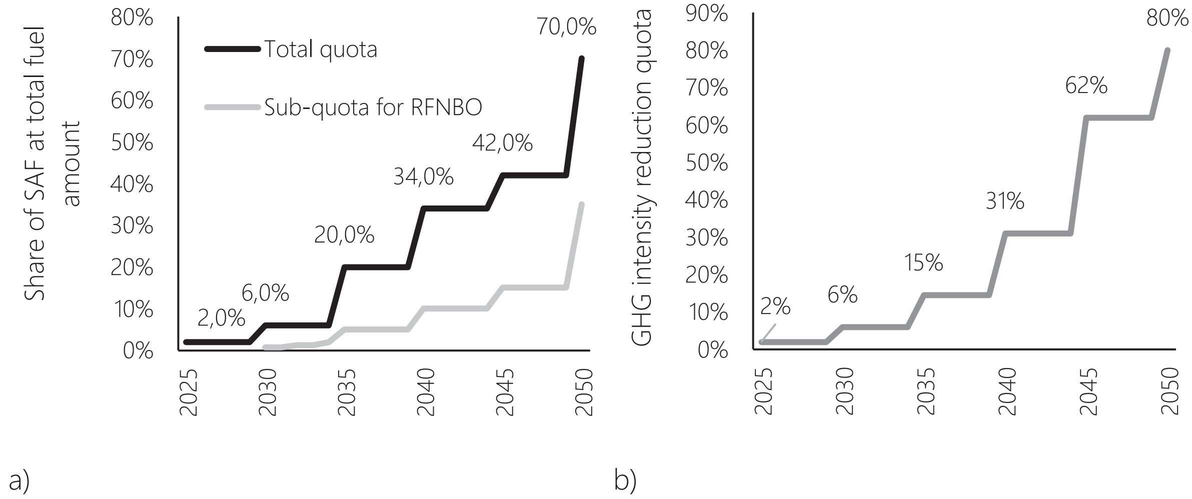

Fig. 1. Trajectory for blending sub-quota in ReFuelEU Aviation (a) and reduction of GHG intensity according to FuelEU Maritime (b) from 2025 to 2050. [43,45].

must be included in the respective balance. Due to these high uncertainties, FEMA is not considered further in this study.

2.2. German legal framework

2.2.1. Climate change act. For Germany, the overarching framework addressing GHG reduction is the national Climate Change Act (“Klimaschutzgesetz”, KSG), setting an overall goal for Germany as well as sector-specific sub-targets [51]. Based on this national legal framework, the transport sector must achieve a reduction of GHG emissions of 42% until 2030 relative to the 1990 situation [51]. For the period from 2030 to 2045, no sector-specific targets are given. Nevertheless, the overall target to transform Germany into a climate-neutral national economy by 2045 is declared. The system boundaries of the KSG only include GHG emissions from the national transport sector, i.e.,

- road transport,
- rail transport,
- inland shipping and
- national part of aviation and maritime transport.

For the KSG, a Tank-to-Wake approach (i.e., only GHG emissions are counted that occur, e.g., during the operation of an internal combustion engine and leave the car via the exhaust pipe) is used to account for the national GHG emission inventory; i.e., upstream GHG emissions are excluded. Thus, for example, renewable fuels are not included at all within the GHG emission balance. Different German Federal Ministries are responsible for fulfilling these GHG emission reductions for their respective sector. Following the revision of the KSG in the year 2024, sectoral targets may be missed if total GHG emissions across all sectors / within the overall economy continue to follow the KSG target reduction path (Fig. 2).

2.2.2. Federal immission control act. The RED must be adapted into national law by the respective member states. In Germany, the corresponding law is the Federal Immission Control Act (BImSchG, German: “Bundes-Immissionsschutzgesetz”) as well as the corresponding ordinances [52–55]. Today, the BImSchG is the national adaptation of the RED II and the respective adaptation of the RED III has not been published yet (June 2025). In Germany, a GHG reduction quota (GHG quota) is used instead of the share for renewable energies set out in the RED II as the target for 2030. The GHG quota is similar to the newly introduced reduction quota of the RED III, however, enables the use of multipliers for certain fuels (Table 2). Aside from these methodological differences, the BImSchG includes the limits of the RED (i. e., the maximum share of 4.4% for biofuels produced from feed and food crops and 1.9% for biofuels produced from feedstock listed in RED III Annex IX part B (exceeding the 1.7% limit granted by the EU)). Until the year 2030, the GHG quota rises up to 25% and was designed to exceed the share of renewable energies of the RED II. However, the GHG quota includes a mechanism that can be triggered depending on the amount of electricity accounted towards the quota. The defined amounts gradually increase up to 88 PJ/a in 2030; if these annual limits are exceeded, the GHG quota can be raised by 0.5 to 1.5 times the emission reduction of the surplus electricity for all following years from 2 years after the exceedance.

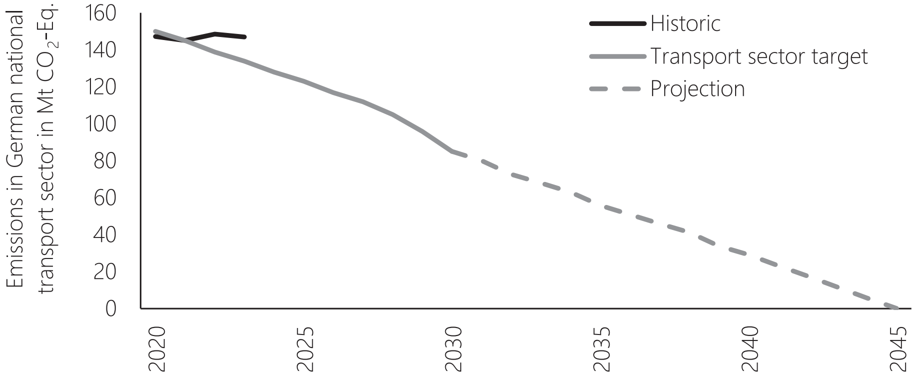

Fig. 2. Emission targets for the national transport sector according to [51] (sector target after 2030 via linear extrapolation derived from overall target).

Table 2
Various options for the German GHG quota as well as limits, mandatory sub-quotas and corresponding multipliers for the year 2030. (RFNBO – renewable fuels of non-biological origin (including hydrogen and derivatives)[52–55].

Fuel option	Limit	Sub-quota	Multiplicator
Biofuels			
from food and feed crops	4.4		1.0
from feedstock listed in Annex IX part A [1]		2.6	1.0 / 2.0
used in maritime sector			
used in aviation sector			
from feedstock listed in Annex IX part B	1.9		1.0
RFNBO			3.0
used in maritime sector			
used in aviation sector			
Renewable electricity			
used in road sector			3.0
used in rail sector			

[1] Those amounts exceeding the mandatory sub-quota can use the accounting factor 2.

3. Transport sector in Germany

The German transport sector comprises the sub-sectors of road and rail transport, as well as aviation and maritime transport. GHG emissions within this diverse transportation sector are primarily caused by the combustion of fossil fuels. However, unlike the chemical industry, these fuels are not used as a raw material / a feedstock, but only as a source of energy for the actual service: the transportation of people (measured in passenger-kilometres) or goods (measured in tonne-kilometres). So far, the transportation of people consumes clearly more energy and is thus more GHG intensive in Germany; i. e., the energy demand for passenger transport is 2.4 times higher than for freight transport [56].

The German transport sector contributes 22% to the total GHG emissions of Germany [57]. Road transport is the largest contributor with 80%. [56] Despite moderate improvements in fuel efficiency, GHG emissions from road transport have remained largely stable over the past decade. This is primarily due to a clear growth in vehicle stock as well as the increasing overall transport activity, which offset technological gains [58,59].

While total transport sector GHG emissions showed only minor variation over time (Fig. 3), a notable decline occurred after the year 2020. However, this drop is largely attributable to the COVID-19 pandemic and subsequent economic effects, including those linked to the Russian invasion of Ukraine [60].

GHG emissions from air transport increased slightly over time but dropped sharply during the pandemic years. Maritime transport (i e., international shipping) showed a decreasing trend even before 2020 and has remained relatively stable in the last decade. Rail transport GHG emissions have remained low and largely unchanged due to the already high degree of electrification. (National) Shipping contributes only marginally to total GHG emissions and has also remained constant. [56] With regards to the energy demand of the sub-sectors, road transport comprises about 81% of the total energy demand of the overall German transport sector, followed by aviation (16%), maritime (3%) and rail transport (2%). In 2023, the total energy demand of the German transport sector was 2500 PJ [56].

Renewable fuels (here: biofuels) have already been used for several years in Germany (Fig. 4) [6,62]. This biofuel consumption today is mostly driven by the legal framework and only to a small extent due to economic reasons; especially until 2030, the detailed frameworks of the RED – and subsequently the national adaptation of the RED in Germany – are the main drivers for the usage of biofuels [6]. However, the resources of the biofuels used changed over time. After the introduction of the RED II, the largest share was given by biofuels from food and feed crops, in Germany, especially based on palm oil. In later years, first palm oil-based biofuels were reduced and in 2023 subsequently phased out completely in Germany and the latest trend is showing an increasing usage of biofuels based on waste and residues according to the definition of resources in RED III Annex IX [63].

4. Methodology

4.1. Assessment approach

The assessment approach (Fig. 5) can be divided into three methodological steps necessary for the goal defined in Chapter 1.

- First, BEV fleet ramp-up trajectories are modelled based on various diffusion models. These BEV ramp-ups are each fitted into the existing vehicle stock (or, respectively, the extrapolation of the latter), which is adapted according to the assumed boundary conditions for the vehicle fleet (column 1 in Fig. 5).
- Then, the corresponding energy demand of the respective composition of the vehicle stock is determined. When combined with the energy demand for the non-road sub-sectors, the overall energy demand of the transport sector (per sub-sector) is available (column 2 in Fig. 5).
- Based on this information, the requirements related to the legal framework (i.e., is (column 3 in Fig. 5). The regulatory analysis includes the European and German frameworks. In the following, the methodological approach of the columns is given in detail.

Below, these various steps are explained in detail.

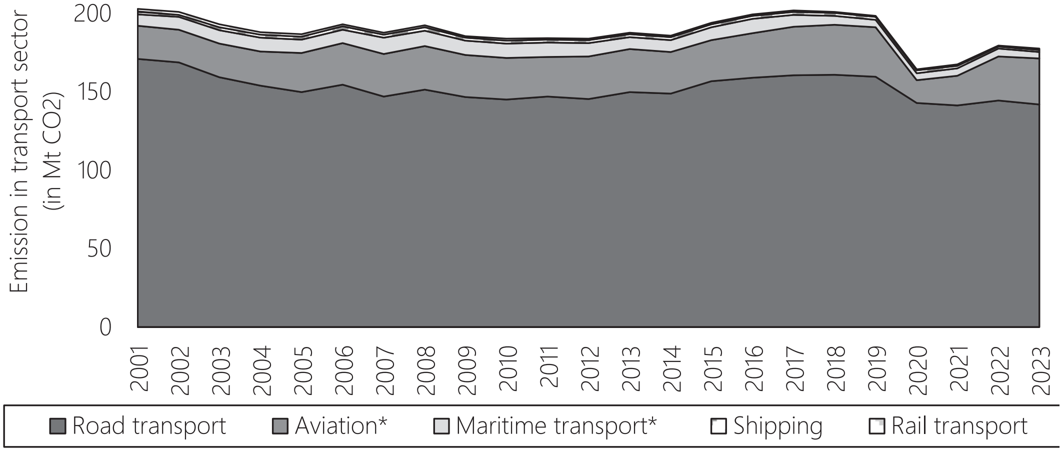

Fig. 3. Historic GHG emissions of the German transport sector for the period 2001 to 2023. (* emissions based on own calculations). [61,56,3].

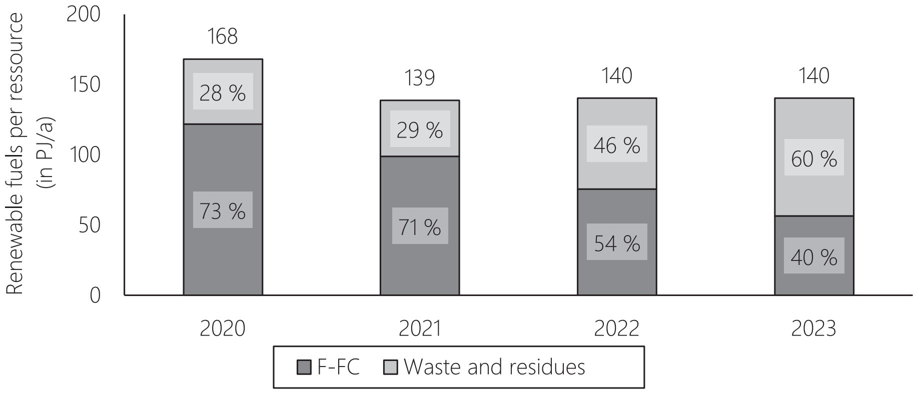

Fig. 4. Historic usage of renewable fuels in Germany from 2020 to 2023 per resource category. (F-FC – Biofuels from food and feed crops, Waste and residues – Biofuels from feedstock listed in RED III Annex IX [6,44]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

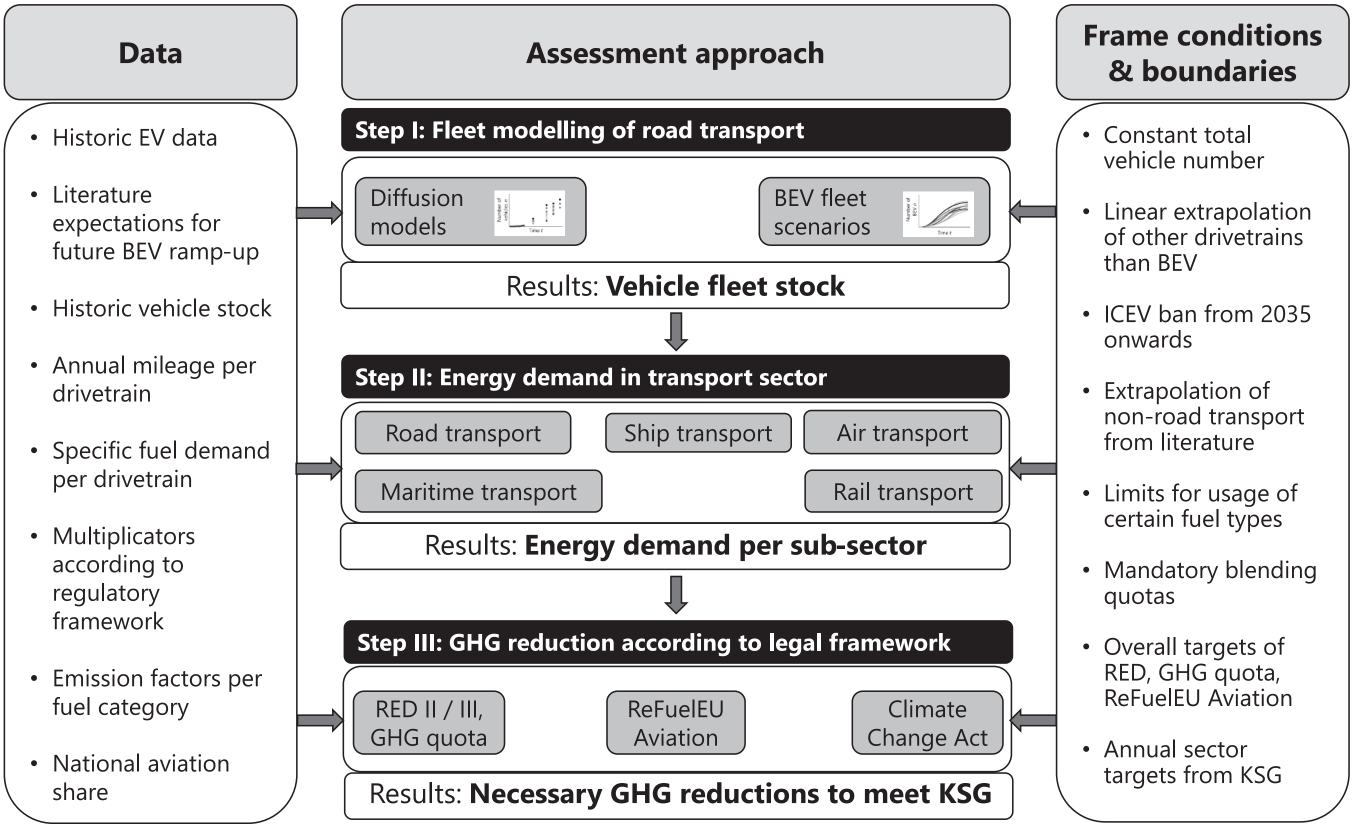

Fig. 5. Schematic assessment approach.

4.1.1. *Fleet modelling of road transport*

To model the BEV ramp-up, the diffusion models are applied to provide the (cumulated) number of vehicles in the fleet stock N. The appropriate growth parameters of the respective modelling approaches for the ramp-up scenarios of BEV are determined by minimizing the deviation of the sum of squared errors (SSE) from the literature-based expectations. In case of a scenario solely based on historic data, for each year t, the difference of the historic or respectively the literature data point $D(t)$ and the modelled data point $N(t)$ (i.e., the cumulated BEV stock) is included (Eq. 1). The literature data (and the modelled value) is included in the sum of squared errors.

$$SSE = \sum_{t} (D(t) - N(t))^2 \tag{1}$$

Based on the sum of squared errors, the best-fitting diffusion model is selected. In the following, for the three diffusion models, two growth parameters a and b are considered. Additionally, the market share M is given by the assumed maximum share of BEV in the fleet stock and represents the upper boundary of all three diffusion models. While the incline of the growth of BEV for the logistic function (LF) (Eq. 2) and the Gompertz model (GM) (Eq. 3) is only based on the market share (with a given set of growth parameters) and the respective year t of the ramp-up, the Bass diffusion model (BDM) is defined recursively by including the realized market share of the previous year $N(t-1)$ (Eq. 4) [26,28,31,33].

$$N(t) = \frac{M}{1 + e^{-(a+bt)}} \tag{2}$$

Table 3
System boundaries per sub-sector for the legal frameworks of the RED (II/III), German GHG quota and the German KSG.

	RED II	RED III	Nat. GHG	KSG
Road	⬜	⬜	⬜	⬜
Rail	⬜	⬜	x	⬜
Shipping	⬛	⬜	⬛	⬜
Nat. Aviation	o	⬜	⬛	⬜
Maritime	o	⬜	⬛	⬛
Int. Aviation	o	⬜	⬛	⬛

⬜ - Included ⬛ - Excluded x - Partially included o - Options used can be included

$$N(t) = M\, e^{-ae^{-bt}} \tag{3}$$

$$N(t) = N(t-1) + a(M - N(t-1)) + \frac{b}{M} N(t-1)(M - N(t-1)) \tag{4}$$

The respective BEV ramp-up according to the selected diffusion model is then integrated into the existing vehicle fleet for the period 2025 to 2050. In general, the drivetrain technologies other than BEV are extrapolated into the future until 2050 and added to the already modelled BEV ramp-up.

4.1.2. Energy demand of the transport sector

4.1.2.1. Road transport. To determine the energy demand of the road sector based on the total number of vehicles $N_{DT,i}$ (differentiated by the fuel or energy carrier used, e.g., diesel or electricity), the respective annual mileage $m_{DT,i}$ and the specific consumption $c_{DT,i}$ are needed (Eq. 5). Additionally, for plug-in hybrid vehicles (PHEV) the share of electric driving $s_{el,DT,i}$ is considered to split the overall energy demand of these vehicles into the different fuel types. For missing data, linear interpolations are realized.

$$E_{\text{Road},i} = \sum_{DT,i} N_{DT,i}\, m_{DT,i}\, c_{DT,i} \tag{5}$$

4.1.2.2. Non-road transport. Road transport accounts for the largest share of total energy demand in the transport sector. However, the regulations presented also apply to parts or even all of the remaining transport sub-sectors. Because the sub-sectors of rail transport, shipping, aviation and maritime transport are not modelled in detail, these sub-sectors, the energy demand of these sub-sectors is based on literature data, whereby linear interpolations are used in between the years of given key data.

For the aviation sector, a distinction between national and international aviation is necessary due to the system boundaries of the different legal frameworks. Although no energy data is available from official sources, the share is derived from the emission balances using the Tank-to-Wake emission factor [64].

4.1.3. GHG emission reduction according to the legal frameworks

The analysis of the degree of fulfilment of the goals defined within the respective regulatory framework is based upon the developed scenarios, as the GHG emission balance is strongly linked to the energy demand. However, the modelled fleet compositions are not the sole aspect to consider. Besides the electrification of drivetrains, the use of renewable fuels is another option to reduce GHG emissions. Both for the EU and also for Germany, the legal framework gives restrictions and mandatory sub-quotas that mainly determine the usage of renewable fuels in the transport sector.

As the different legal frameworks use different balancing references, the system boundaries used for the respective framework can be found in Table 3. The only framework including all sub-sectors (i.e., also the international transport) is the RED III The KSG accounts all sub-sectors, yet only the national emissions of the aviation and the shipping sectors. In the RED II, only the road and rail transport are balanced with regards to the mandatory sub-quota and the overall target. Nevertheless, the options of advanced biofuels and RFNBO used within the maritime or aviation sector can be counted towards the share of renewable energies used in transport sector. The German GHG quota, however, excludes maritime and aviation sectors completely. Also, the electricity used within rail transport is excluded, yet, other fuels used are included in the overall balance.

4.1.3.1. EU. For the RED III, the two different target metrics, the GHG quota or the share of renewable energies within the transport sector, can be used.

- The GHG quota is calculated according to (Eq. 6), whereby $E_{i,EE}(t)$ represents the lower heating value of the renewable fuels assumed, $e_{i,EE}(t)$ the respective GHG emission factor of the renewable fuel and $e_{R,i}(t)$ the respective fossil reference value at the year t. The reference $E_{i,EE+F}(t)$ corresponds to the total fuel consumption, regardless of whether it is of fossil or of renewable origin [44]. The RED III uses WtW emission factors for the GHG quota (with the exception of renewable electricity).

$$GHG(t) = \frac{\sum_i E_{i,EE}(t)\,\left(e_{R,i}(t) - e_{i,EE}(t)\right)}{\sum_i E_{i,EE+F}(t)\, e_{R,i}(t)} \tag{6}$$

- The share of renewable energies is calculated by the ratio of the lower heating value of the renewable fuels used $E_{i,EE}(t)$ and the total fuel consumption $E_{i,EE+F}(t)$ (Eq. 7). However, a crediting factor CF_i can be taken into account (Table 1)[44] (see also Annex A.1 for more information about the crediting factors).

$$SRE(t) = \frac{\sum_i E_{i,\text{EE}}(t)\, CF_i}{\sum_i E_{i,EE+F}(t)} \tag{7}$$

In both cases, only electricity from renewable energy sources is counted towards the overall target. Therefore, the creditable electricity $E_{El,EE}(t)$ is calculated based on the average share of electricity from renewable energy within the respective Member State (here: Germany) over the last two years $\bar{s}_{EE}(t)$ (Eq. 8).

$$E_{El,EE}(t) = E_{El}(t)\, \bar{s}_{EE}(t) \tag{8}$$

4.1.3.2. Germany. For Germany, it is differentiated between the GHG quota of the current national adaptation of the RED II and the emission balance of the national Climate Change Act.

- In terms of the GHG quota $GHG_{RED\ II}(t)$, the calculation is similar to the European GHG quota of the RED III; however, both fossil and renewable fuels are balanced against a fossil reference (Eq. 9) [63]. The German GHG quota uses WtW emission factors as the RED III GHG quota.

$$GHG_{RED\ II}(t) = \frac{\sum_i E_{i,EE+F}(t) \cdot CF_{i,GHG}\ (t) - e_{i,EE+F}(t)}{\sum_i E_{i,EE+F}(t)\ e_{R,i}(t)} \tag{9}$$

- For the national Climate Change Act (KSG), the emission balance $KSG(t)$ is calculated by accounting all fossil fuel-based GHG emissions in the national transport sector (Eq. 10), whereby $E_{i,F}$ is the amount of fossil fuels used in the respective year t and $e_{i,F}$ the respective Tank-to-Wake (TtW) GHG emission factor of the fossil fuel [7]. Emissions from renewable fuels (both biofuels and RFNBO) as well as electricity are not included in the GHG emission balance.

$$KSG(t) = \sum_i E_{i,F}\ e_{i,F} \tag{10}$$

4.2. Data and assumptions

The modelling of the deployment of BEV requires a parallel modelling of the remaining vehicle fleet to determine the corresponding energy demand in the road transport sector. Due to the variety of ramp-up scenarios, a simplified approach is necessary to limit computational effort.

4.2.1. Fleet modelling of road transport

The chosen approach is based on historic data of the BEV ramp-up in Germany until 2024. However, as the available data cover only a short period of time, extrapolations solely based on this dataset are characterized by high insecurities. Therefore, intermediate fleet targets based on literature data and government targets are used (e.g., $15 \cdot 10^6$ BEV by 2030 as proclaimed by the German government) [63,65]. Additionally, the market potential is varied from 70 to 100% of the vehicle number of the respective vehicle category (e.g., passenger cars) and assumed as the ramp-up value for 2050.

Besides the BEV share of the total vehicles, the speed of the ramp-up is important as well, e.g., a late but steep incline close to the year 2050 would have different implications on the renewable fuel strategy than an early, moderate incline. From the literature ranges given in Table 4, a set of ten scenarios is developed, which represent different kinds of ramp-ups. S1 is designed without additional fleet targets, only the market potential in 2050. For the overall market potential of the total vehicle count of the different vehicle segments, three assumptions for 2050 of 100%, 85% and 70% of the total vehicle count are investigated. Additionally, for each assumption of the market potential, three different ramp-up trajectories are selected from the literature ranges for the years representing an early, a late and an intermediate incline of BEV. The resulting input for the diffusion models in order to retrieve the ramp-up curves for BEV is given in Fig. 6.

Table 4
Assumptions for the BEV ramp-up based on historic data of Germany.

Year	2030	2040	2045	2050
	Passenger / commercial vehicles (% of market potential)[1]	Passenger / commercial vehicles (% of market potential)[2]	Passenger / commercial vehicles (% of market potential)[1]	Passenger / commercial vehicles (% the total vehicles)[2]
S1	–	–	–	100%
S2	16% / 9%	30% / 30%	65% / 37%	100%
S3	18% / 19%	55% / 60%	76% / 85%	100%
S4	29% / 33%	80% / 90%	86% / 98%	100%
S5	16% / 9%	30% / 30%	65% / 37%	85%
S6	18% / 19%	55% / 60%	76% / 85%	85%
S7	29% / 33%	80% / 90%	86% / 98%	85%
S8	16% / 9%	30% / 30%	65% / 37%	70%
S9	18% / 19%	55% / 60%	76% / 85%	70%
S10	29% / 33%	80% / 90%	86% / 98%	70%

[1] Based on [20-25], [2] Own assumptions.

Thus, a set of ramp-up scenarios is modelled to reflect the range of possible developments in the electrification of road transport. For subsequent in-depth analyses – particularly those concerning the legal frameworks – three representative scenarios are selected that illustrate a slow, medium, and fast ramp-up of BEV. The selection is based on the total electricity demand in road transport, including both BEV and the electric driving share of PHEV. For each year from 2025 to 2050, the electricity demand of all scenarios is compared to the mathematical minimum, median, and maximum across all scenarios. The scenarios selected for further analysis are those whose time series deviate least from the respective reference trajectory, based on the sum of squared errors over the entire time horizon. This approach ensures that the selected scenarios accurately reflect the lower, central, and upper bounds of electricity demand in road transport over time. The selected scenarios are subsequently referred to as the minimum (S9), median (S5), and maximum (S4) cases.

4.2.2. Energy demand of transport sector

4.2.2.1. Road transport. The drivetrains considered are listed in Table 5. The non-BEV drivetrains are extrapolated based on their trend from historic data (2020 to 2023). As a boundary condition, the overall number of vehicles for the year 2023 is kept constant.

An exception is made for the predominant vehicles (i.e., vehicles with diesel or petrol engines in the passenger car segment and for commercial vehicles with diesel engines). For these, the difference between the target number of vehicles and the sum of the other drivetrain technologies is calculated and (if applicable) distributed proportionately.

If the sum of BEV and other drivetrains is lower than the current vehicle count, FCEV are increased as a buffer. If the sum exceeds the current vehicle number of the respective segment, vehicles are reduced in the following way and order.

- First, the predominant drivetrains are reduced; in the case of passenger cars, gasoline and diesel vehicles are reduced according to their respective share in the vehicle stock.
- If no more vehicles of the previous category remain, drivetrains with a negative trend are reduced beyond their extrapolated rate (compressed natural gas (CNG) / liquefied natural gas (LNG) and liquefied petroleum gas (LPG) vehicles).
- After that, vehicles with a positive trend are reduced until the total vehicle count is in balance ((plug-in) hybrid vehicles ((P)HEV)).

An additional constraint is introduced by considering the current EU legislation concerning CO_2 fleet limits for OEM; i.e., no vehicles with an ICE can be added to the vehicle stock from 2035 onwards for passenger cars as well as light duty vehicles and from 2040 onwards for utility vehicles (for utility vehicles, the 90% CO_2 emission reduction is treated as a ban) [47,68]. In terms of modelling, all ICEV (including hybrid vehicles) are kept constant from the respective year onwards, if no reduction according to the rules above is necessary.

In certain scenario combinations, a gap may arise where fossil fuel-driven drivetrains (e.g., diesel and gasoline) have already been phased out, but the total number of vehicles has not yet been met. In this case, fuel cell vehicles (FCEV) are used to fill the gap.

To determine the energy demand from the vehicle stock, the mileage

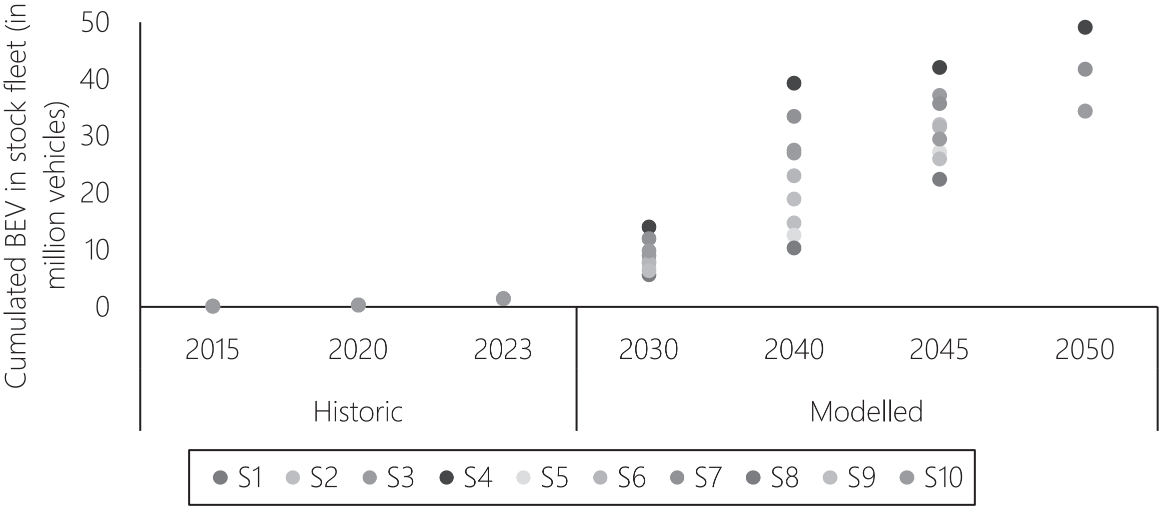

Fig. 6. Scenarios for ramp-up curves for BEV in the passenger vehicle segment from 2025 to 2050. (Data: [20–25,66,67], own assumptions).

Table 5
Overview of the groups and individual drivetrains considered.

Group	Drivetrain technology / fuel type	Abbreviation
ICEV	Diesel	–
	Gasoline	–
	(Compressed / Liquefied) Natural gas	CNG / LNG
	Liquefied petroleum gas	LPG
	(Mild) Hybrid vehicles	HEV
	Plug-In hybrid vehicles	PHEV
ZEV	Battery electric vehicles	BEV
	Fuel cell electric vehicles	FCEV

is derived from [56] and kept constant for the considered period, while both consumption and the share of electric driving are based on [21]. The assumptions concerning mileage and fuel demand are given in Annex A. [22,23,56,66].

4.2.2.2. Non-road transport. For the non-road sub-sectors, the data is based on [66,67], which is the official basis for the emissions balance and, in the case of rail transport, [22,23] is used as [67] gives no sufficient differentiation for the energy demand of the rail transport. For the distinction between national and international aviation, the share of national aviation is derived from [56,64]. If the energy demand is not split into the different fuel options, the distribution of [21] is used.

4.2.3. GHG emission reduction according to the legal framework

Several assumptions are necessary in order to evaluate the legal frameworks at the EU and the German levels against each other. First, it is assumed that 100% of the modelled electricity demand is counted towards the different quotas, as the fossil reference for several of the considered frameworks is also based on the final energy used within the transport sector and any misfit here would lead to a change in the total energy demand. Between the different scenarios, no effect on the composition of the grid electricity is assumed, i.e., no change of the emission factor is considered. Outside of the legislative limitations, no further restrictions are implemented concerning the usage of renewable fuels.

The obligations of the legal framework are and will be fulfilled (at least in parts) by blending renewable fuels with fossil fuels – besides mandatory blending or GHG quotas, the amounts of renewable fuels used are mainly determined based on economic reasons. Due to the complexity in modelling, a cost-based selection model is not considered here and therefore, an assumption for the specific order of usage for the different renewable fuels must be made. [6] shows, that biofuels based on feedstocks listed in RED III Annex IX part B as well as biofuels from feed and food crops are already used today. Also, advanced biofuels, produced from feedstock listed in RED III Annex IX part A, are used to a certain degree (e.g., biomethane). However, especially liquid advanced liquid biofuels (e.g., ligno-ethanol, Fischer-Tropsch-based biofuels) are not available in large quantities yet [6,69]; the same is true for RFNBO [69]. Across legal frameworks, the order of usage is therefore defined as mandatory sub-quotas or blending obligations (advanced biofuels, RFNBO, ReFuelEU Aviation),

- electricity (in road and, if applicable, rail transport),
- biofuels based on feedstocks listed in RED III Annex IX part B,
- biofuels based on food and feed crops,
- RFNBO hydrogen and
- advanced biofuels or liquid RFNBO.

This order of usage is also considered within ReFuelEU Aviation, i.e., within the blending quota for SAF produced from feedstock listed in RED III Annex IX, SAF from feedstock listed in RED III Annex IX part B is used until the overall limit is reached, before SAF from feedstock listed in RED III Annex IX part A are assumed.

5. Results

The results are divided into modelling the BEV ramp-up and fleet composition as well as of the energy demand and the subsequent impact on GHG emissions in the transport sector. The GHG emissions are evaluated against the background of the different regulatory frameworks.

5.1. Fleet modelling of road transport

5.1.1. Results

The modelling of the BEV ramp-up is differentiated between passenger cars and utility vehicles, while the latter are further divided into light-duty vehicles and larger trucks and busses.

- The ramp-up of passenger cars in road transport is shown in Fig. 7. By 2030, the number of BEV ranges between 4.5 and 14.3 · 10^6 vehicles, increasing to between 18.3 and 38.5 · 10^6 in 2040, and reaching 31.3 to 48.7 · 10^6 of a total of 49.1 · 10^6 vehicles in 2050. In the median scenario S5, a number of 6.5 · 10^6 BEV are reached by 2030, increasing to 33.1 · 10^6 in 2040 and 41.4 · 10^6 by 2050. While the strongest growth in market share can be found for BEV, HEV and PHEV also increase moderately. Other drivetrain types, such as LPG

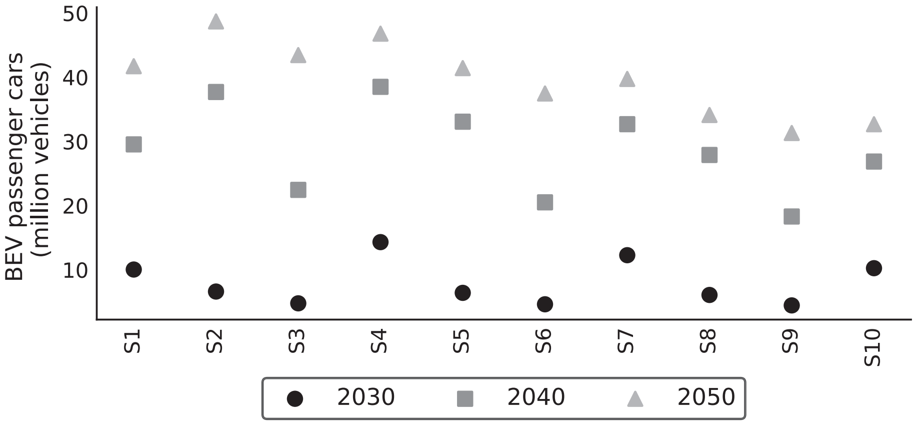

Fig. 7. Overview over modelled BEV ramp-up scenarios for passenger cars and utility vehicles for the years 2030, 2040 and 2050.

and CNG vehicles, remain insignificant throughout the entire modelling period. In the median scenario S5, gasoline and diesel vehicles, along with LPG and CNG, are fully phased out by 2045. By 2050, the remaining vehicle stock in S5 consists of $5.1 \cdot 10^6$ HEV and $2.5 \cdot 10^6$ PHEV alongside the BEV out of a total of $49.1 \cdot 10^6$ vehicles.

- The ramp-up of electric drivetrains in utility vehicles of the segment light-duty vehicles is similar to that of passenger cars. Until 2030, 0.27 to $1.1 \cdot 10^6$ vehicles are BEV. In this segment, 0.5 to $2.9 \cdot 10^6$ battery electric vehicles are in the fleet stock, depending on the respective scenario. Until 2050, the range is given by 2.1 to $3.2 \cdot 10^6$ vehicles. For the rest of the utility vehicles, the cumulated amount of BEV in the stock fleet ranges from 17,500 to 265,000 vehicles in 2030. For the year 2040, the scenarios range from 92,000 to 715,000 vehicles and in 2050, from 350,000 to 785,000 BEV.

For the in-depth analysis of the modelled bandwidth, the three representative scenarios are investigated further. For the passenger car segment, the ramp-up for these scenarios is shown in Fig. 8. Besides the total vehicle count in the stock fleet, the average annual growth is given (i.e., the 5-year-average of annual growth of the BEV segment within the vehicle stock per year).

The plot visualizes the different maximum potentials reached in 2050, but, in terms of the average annual growth, highlights not only the speed of the ramp-up itself, but also the time at which it occurs. On the left side of the plot, the different trajectories can be observed (i.e., not only the absolute vehicle count in 2050, but also the pathway leading to the latter).

Following these ramp-up scenarios, the fleet stock composition for passenger cars in the median scenario S5 is given in Fig. 9. BEV become most dominant in the fleet from 2037 onwards. As the total number of vehicles is kept constant by assumption, the growing share of BEV leads to an accelerated phase-out of other drivetrains in the prescribed order: first pure ICE vehicles, followed by LPG and CNG as well as HEV and PHEV.

5.1.2. Discussion

Although there are differences in speed, timing and maximum market share, all scenarios considered introduce large quantities of BEV into the fleet stock and BEV make up for the largest share in the fleet stock until 2050. By this, other drivetrains are affected, i.e., also those with positive trends from historic data (i.e., increasing vehicle counts) are reduced in the model to keep the number of total vehicles balanced. Additionally, the ICEV ban starting in 2035 prohibits a further increase of these types of vehicles, including HEV and PHEV.

Differences between the scenarios, however, can be identified with respect to the annual growth rates shown in Fig. 8. Especially for the maximum scenario S4, nearly all newly registered vehicles would need to be BEV to meet the modelled ramp-up from 2030 onwards, compared the historic average of $3.4 \cdot 10^6$ new registrations per year (2015 till 2020) in the period until 2040 [70].

The speed of the different ramp-ups is highlighted by the change in the average annual growth: For the median scenario S5, the annual growth increases strongly after 2030, leading to clearly increased total vehicle numbers within the stock fleet. In contrast, the minimum scenario S9 reaches a lower BEV count in 2050, but the increase in speed is significantly later and less significant than in the median scenario (S5). The maximum scenario S4 shows an even more accentuated ramp-up. In 2030, BEV are roughly doubled compared to S5 shown by a significantly higher average annual growth. This annual growth even increases for the period 2035 to 2040, before the growth slows down and the BEV fleet in this scenario is asymptotically approaching the 2050 value.

The historic number of new registrations per year in the last decade can be used as a comparison of the “effort” of the different scenarios.

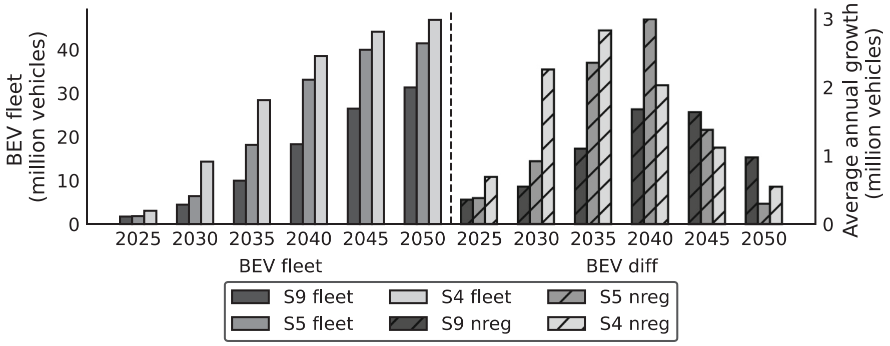

Fig. 8. Cumulative BEV fleet and average annual growth for passenger cars from 2025 to 2050 for scenarios S9, S5 and S4. (S9 – Minimum scenario, S5 – Median scenario, S4 – Maximum scenario, fleet – Absolute number of BEV in fleet stock, nreg – Average annual growth of BEV fleet).

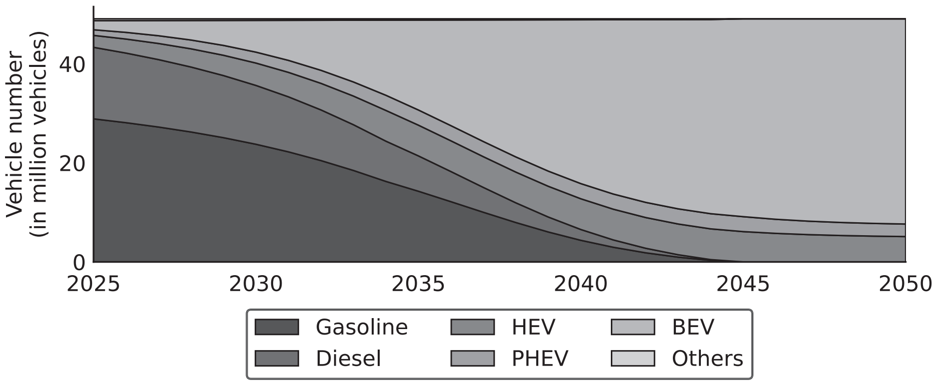

Fig. 9. Fleet composition between 2025 and 2050 for the median scenario S5. (Others: LPG, CNG/LNG, FCEV) (HEV – Hybrid electric vehicle, PHEV – Plug-In hybrid electric vehicle, BEV – Battery electric vehicle, LPG – Liquefied Petroleum Gas, CNG/LNG – Compressed / liquefied natural gas, FCEV – Fuel cell electric vehicle).

After 2020, due to effects of the pandemic, the energy crisis connected to the Russian invasion of Ukraine as well as the ongoing effects of the former events on the economic situation results in a reduction of the annual new registrations to around $2.8 \cdot 10^6$ vehicles in the years 2020 to 2024 [70–72]. Compared to the average annual growth rates of the modelled scenarios, in all three cases BEV would need to become dominant in terms of new registrations at one point or another. Especially, as the shown average annual growth rates would need to be even higher to reach the total vehicle count due to the decommissioning of vehicles.

Decommissioning can occur for a variety of reasons, e.g., crashes, export or the end-of-life of a vehicle; if the owner of such a car wishes to continue using their own car for their individual mobility, these vehicles also appear again in the new registrations (i.e., when a new car is purchased (directly or indirectly) as a replacement (without considering the increase of car owners in total)). No specific decommissioning rate is assumed here; however, the issue is addressed indirectly, e.g., by the limitation for ICEV to remain constant at most after the ICEV ban in 2035 (i.e., without positive gradients for the respective drivetrain in the fleet stock).

None of the scenarios shown is likely to happen without beneficial factors (i.e., favourable policies and/or strong economic incentives for the consumers to switch from ICEV to BEV). This also includes the corresponding availability of charging infrastructure (which is not considered in this study, but poses an important requirement for BEV), as the roll-out of BEV into the mass market and also into market dominance requires widely available charging options to accommodate the present mobility behaviour (as no fundamental change in mobility is assumed) [20,25].

5.1.3. Placement

The ramp-up of the BEV fleet in the vehicle stock is based on literature values differing both in the overall BEV share projected by 2050 and in the timing of the most significant market penetration. Compared to this, the curve fits of the diffusion models derived from historical data tend to result in slightly lower trajectories. Since the optimization is based solely on minimizing the least square error, this deviation cannot be attributed exclusively to model limitations or errors.

The considered studies emphasize the importance of an early BEV ramp-up to achieve long-term decarbonization targets or to meet certain milestones (e.g., $15 \cdot 10^6$ battery electric passenger cars in 2030) [20–25]. This is due to the slow turnover of the vehicle stock (i.e., the gradual replacement of ICEV with BEV) being constrained by two main factors:

- Rising average vehicle age. In Germany, the average age of the passenger car fleet increased in recent years. This implies that vehicles remain in use for longer periods, thereby delaying fleet renewal and slowing the integration of BEV [56].
- Limited annual registrations. The number of new vehicles registered each year sets an upper limit on how quickly BEV can enter the fleet and replace existing ICEV [73].

In light of these constraints, the actual BEV ramp-up observed in German fleet statistics up to today, both in terms of absolute BEV share in the fleet stock, but also the share in new registrations, lags behind the more ambitious trajectories presented in literature [20–25]. All studies highlighted that considerable efforts are necessary to reach the respective BEV ramp-up – also based on policy measures that have not been implemented yet [20,21,25]. The majority of studies have been published in 2021 and are therefore based on an even earlier vehicle stock, leading to a slower ramp-up with regard to the considered literature.

Fuel cell electric vehicles (FCEV) are not projected to grow significantly, as the extrapolation of historic data does not support a substantial uptake [73]. However, in scenarios with fewer BEV after 2035, and given the inability to introduce new ICE vehicles, FCEV are used to balance the fleet size. Nevertheless, FCEV do not comprise a significant role in the scenarios considered.

This development is a result of the model structure but could reflect real-world circumstances where BEV availability is limited or user preferences favour FCEV due to perceived advantages such as refuelling speed or range – despite the general expectation in literature that FCEV will play only a minor role in the passenger car segment [25].

5.2. Energy demand in transport sector

5.2.1. Results

To investigate the GHG emissions of the transport sector, the energy demand of the overall transport sector must be considered. This overall energy demand for the modelled scenarios between 2025 and 2050 decreases for the median from 2400 PJ in 2025 to 1500 PJ in 2050, characterized by a total range from minimum to maximum of 1400 to 1550 PJ in 2050 (Fig. 10). For the road sector, the energy demand in the year 2030 sums up to 1800 to 1900 PJ, 760 to 1200 PJ in 2040 and 750 to 930 PJ in 2050. While the energy demand of road transport therefore decreases by 50 to 60% for the selected scenarios from today till 2050, the energy demand of the overall transport sector decreases only by 35 to 40% due to the non-road sub-sectors. Together, these sub-sectors comprise 550 PJ in 2025 and 625 PJ in 2050 [21,56,67]. Responsible for the increase in the energy demand of the non-road sectors is especially the growing aviation sector. In total, the energy demand of the non-road transport sector increases by 20% until 2050.

The reduction in energy demand is based on the increasing electrification across the scenarios, whereby BEV are increasingly used both in the passenger car segment as well as for commercial vehicles. The

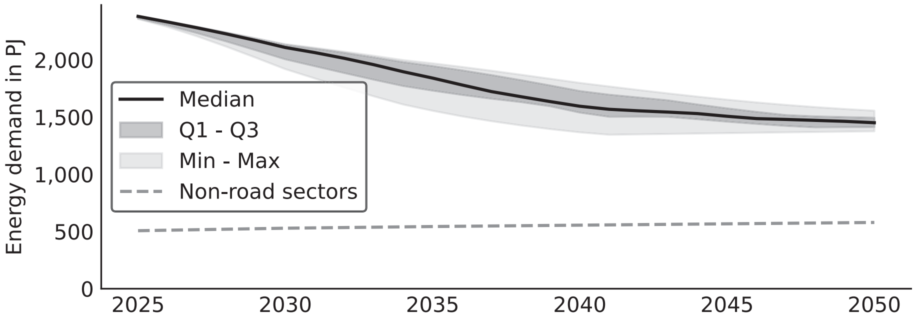

Fig. 10. Overall energy demand for the modelled scenarios from 2025 to 2050. (Q1–25%-Quartile, Q3–75%-Quartile, Min – Lowest value across scenarios, Max – Highest value across scenarios).

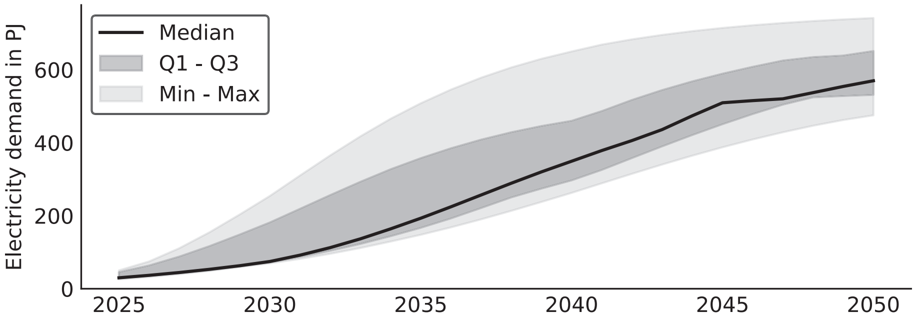

Fig. 11. Electricity demand in the road sector for the modelled scenarios from 2025 to 2050. (Q1–25%-Quartile, Q3–75%-Quartile, Min – Lowest value across scenarios, Max – Highest value across scenarios).

electricity demand in the road sector resulting from the shown BEV ramp-ups increases from 25 PJ in 2025 to 260 to 650 PJ in 2040 and 475 to 750 PJ in 2050 (Fig. 11).

The ratio of electricity used in passenger cars to electricity used in commercial vehicles ranges from 1.3 to 1.9 in 2050.

5.2.2. Discussion

As mileage and total number of vehicles are kept constant within the model (see above), the reduction in final energy demand observed across all scenarios results primarily from the shift towards more energy-efficient drivetrains in road transport, most notably the increasing share of BEV. According to the assumptions for the fuel demand, BEV exhibit significantly higher energy efficiencies compared to conventional ICEV resulting in the fact that their growing share within the vehicle stock directly lowers the total energy consumption of the overall sector [16]. This is true both for passenger cars but also for utility vehicles.

In addition to BEV, PHEV and HEV contribute to energy savings due to their higher drivetrain efficiency.

- HEV, while not externally chargeable, benefit from regenerative braking and improved drive cycle performance, resulting in a reduced fuel consumption [21,74].
- PHEV are assumed to increasingly rely on electric driving over time, which further enhances their contribution to a reduced energy demand.

Finally, gradual efficiency improvements are assumed across all vehicle types, contributing incrementally to the observed decline in sectoral energy demand. However, the effect of the shift in the predominant drivetrain technology is more significant.

The rest of the transport sector, that is not modelled in detail, accounts for 25% in 2025 and 40 to 45% in 2050 as the energy demand of the road sector declines. Depending on the regulatory framework, the rest of transport sector thereby increases in importance over time, as the share at the total energy demand increases, which is the basis for most energy-related sub-quotas.

5.2.3. Placement

The bandwidth of the development of the overall energy demand within the transport sector, corresponding to the developed fleet scenarios, can be compared with similar studies showing similar ranges (Fig. 12) [20–25,66,67].

Nevertheless, for the assessment of the results, several methodological differences must be considered.

- Some published studies explicitly incorporate behavioural changes, such as a modal shift towards more energy efficient transport modes (e.g., rail transport, shared mobility), subsequently reducing motorized individual transport (MIV) [20–24]. These assumed behavioural changes become more significant for the period of 2040 to 2050.
- The metric used to represent the demand for transport services is different. While many studies operate based on passenger-kilometres (p km), this study uses mileage (i.e., vehicle-kilometres). Consequently, factors such as increased occupancy rates (e.g., through car sharing or pooling) can reduce total mileage even if the passenger-kilometres remain constant or increase [21,67].
- Differences in the vehicle stock arise both in terms of composition and the total number of vehicles. Literature includes assumptions of declining [20–25], constant [67], or even increasing vehicle stock levels [24]. However, the resulting energy demand is not only influenced by vehicle number and the drivetrain composition but also by the respective specific energy consumption. This study builds on assumptions related to the fuel consumption derived from [21]. Although not all studies report these assumptions in detail, a comparison with [25] shows that the fuel demand of [21] is higher.

The comparison with literature supports the general plausibility of the modelling approach. However, the availability of disaggregated data

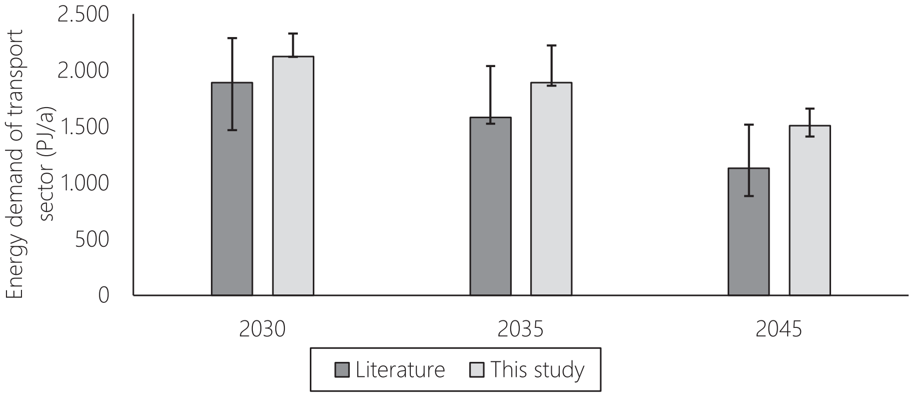

Fig. 12. Comparison of final energy demand in transport sector for the median in literature and this study for the years 2030, 2035 and 2045. (Data: [20–25,66,67], own calculations).

varies across studies, which limits the ability to conduct a detailed comparison on the level of the respective sub-sectors or segments.

5.3. *GHG emission reduction according to the legal framework*

5.3.1. *Results*

The results of the (necessary) GHG emission reduction according to the legal framework are split into two parts: First, the emission reduction due to the obligations of frameworks (e.g., the RED) is determined (due to the obligations for the usage of renewable fuels). Secondly, on this basis, the additional GHG emission reduction necessary to reach the German KSG goals is quantified. For the following analysis, only the representative scenarios are shown.

Fig. 13 shows the GHG emission reduction due to the renewable fuels used within the different regulatory frameworks in 2030. For each legislation shown, the fleet scenarios are analysed in terms of mandatory requirements as sub-quotas or overall targets to meet. Thereby, the respective renewable fuel amount is calculated to meet the overall goal of the respective legislation and “translated” into the emission reductions using the methodology of the KSG. It is differentiated between the fuel categories defined in the regulatory framework (e.g., biofuels from food and feed crops or advanced biofuels from feedstocks listed in RED II Annex IX part A). In all scenarios, it is assumed that 100% of the electricity demand is also balanced within the quotas and energy targets, even if the overall target is exceeded. In this case, the theoretical target is calculated, which would be necessary to accommodate all mandatory quotas and the whole electricity demand.

For the RED II, it can be seen that the overall target of a share of 14% renewable energies is exceeded in all three scenarios. The renewable fuels shown are the mandatory sub-quota for aviation fuels of 5% (of the overall kerosene demand, including international aviation) and the mandatory sub-quota for advanced biofuels of 1.75% in relation to the energy demand in road and rail transport. The mandatory fuel obligations range from 50 PJ/a for the maximum scenario S4 to 60 PJ/a for the minimum (S9) and median scenarios (S5). In terms of GHG emission reduction, the usage of renewable fuels due to the obligations of the RED II translates into an emission saving of 4 Mt. CO_2 in 2030, including SAF.

In the case of the RED III, two available target measures, both addressing the overall transport sector, are differentiated: The share of 29% renewable energies and the GHG quota of 14.5%.

- The minimum scenario S9 and the median scenario S5 achieve the 29% target by the additional usage of renewable fuels, exceeding the category of F-FC and Annex IX B. To fulfil the overall target, the only unlimited category is necessary, which consists of either Annex IX A or RFNBO. The maximum scenario S4 does not exceed the mandatory sub-quotas – the overall balance, including the latter and the electricity demand (and including the multiplicators) leads to a calculated share of renewable energies of 50%. In terms of renewable fuel demand, overall, the scenarios need 230 PJ, 220 PJ or 75 PJ respectively in 2030, which equals a GHG emission reduction of 16 (S9, S5) or respectively 5 Mt. CO_2 (S4).
- The renewable fuel mix for the other possible overall target of the RED III, the GHG quota of 14.5%, is similar. However, the total amount of renewable fuels necessary for the minimum (S9) and the median scenario (S5) are higher; in case of the maximum scenario S4, no additional fuels except the mandatory sub-quotas are necessary to fulfil the target in comparison to a smaller margin than for the share of renewable energies (+0.6% above the target of 14.5%). The GHG quota in the RED III requires the highest usage of renewable fuels with 255 PJ, 250 PJ and 75 PJ for the different scenarios in 2030, which corresponds to 18 Mt. CO_2 (S9, S5) and 5 Mt. CO_2 (S4).

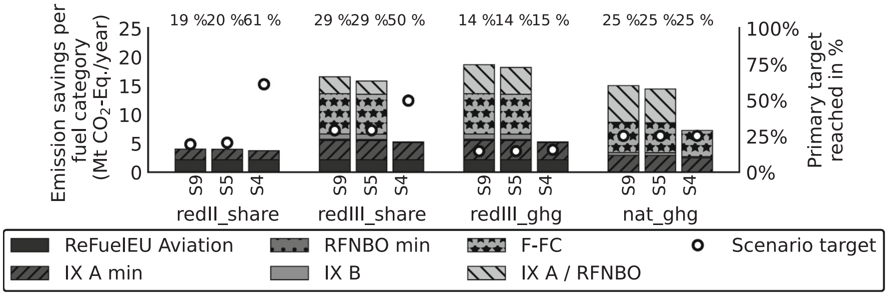

Fig. 13. Renewable fuel usage for the legal frameworks of the RED II, RED III (GHG quota and RE-share) and German GHG quota for the minimum (S9), median (S5) and maximum (S4) scenarios in 2030. (RFNBO – Renewable fuels of non-biological origin, F-FC – Biofuels from food and feed crops, IX A / B – Biofuels from feedstock listed in RED III Annex IX part A / B, Hydrogen – RFNBO Hydrogen) (redII_share – RED II framework, redIII_share – RED III targets (share of renewable energies), redIII_ghg – RED III targets (GHG quota), nat_ghg – National GHG quota in Germany based on RED II framework). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The current national adaptation of the RED II in Germany is comparable to the RED III in terms of renewable fuel usage. However, all three scenarios must use fuels exceeding mandatory sub-quotas. Analogous to the different targets analysed in the framework of the RED III, both the minimum (S9) as well as the median scenario (S5) use the available amount of the limited options (biofuels from food and feed crops, biofuels from feedstock listed in RED III Annex IX part B) and also need the usage within the category of advanced biofuels or RFNBO. For the maximum scenario S4, the usage of the available biofuels from feedstock listed in Annex IX B quantities and additionally, biofuels from food and feed crops, is sufficient to reach the overall target of the 25% GHG reduction quota. The absolute demand for renewable fuels in the German GHG reduction quota sums up to 255 PJ / a GHG emission reduction of 17 Mt. CO_2 in the minimum scenario S9, 245 PJ / 16 Mt. CO_2 in the median scenario S5 and 130 PJ / 9 Mt. CO_2 in the maximum scenario S4 for the year 2030.

However, the overarching framework for Germany is the KSG; the national adaptation of the RED II and the RED III can be considered as mandatory sub-targets that need to be fulfilled (representatively of the minimum requirements of the RED, even with the upcoming revision of the current national adaptation). In this case, this sub-target merely specifies or rather limits how the target is to be met (e.g., that the GHG target must be met, but in addition to that, certain amounts of advanced biofuels must also be used and the GHG reduction shall not only be met by the usage of F-FC). Subsequently, these sub-targets may not transfer directly into the absolute GHG reduction target; however, in total, the KSG goals must be met. Additionally, most regulative frameworks do not exceed the period until 2030 so far and therefore do not cover the whole regulated period of the KSG.

The analysis of the scenarios within the boundaries of the KSG is given in Fig. 14. On the basis of the framework of the RED III (using the methodology of the GHG quota), the necessary overall targets (within the calculation methodology of the GHG reduction quota) are calculated in order to meet the KSG targets for the respective years (see also Annex A.3). For the year 2030, a GHG reduction quota of 28% is necessary to fulfil the obligations of the KSG for the minimum (S9) and the median scenario (S5). In the case of the maximum scenario, no additional fuel usage is necessary to meet the GHG reduction targets of the KSG in 2030. Yet, the GHG quota must be at 19% to fully include all electricity within the quota. For the year 2040, the quota necessary to achieve the GHG emission reduction according to the KSG, the GHG quota would need to be between 71 and 87%, depending on the scenario. For the minimum (S9) and the median scenario S5, it is necessary to incentivize the additional amounts of renewable fuels – in case of the maximum scenario S4, the GHG quota of 87% is necessary to account for all of the electricity within the GHG quota. In 2050, the necessary quotas range from 95 to 98%. The additional renewable fuel demand ranges between 0 PJ to 195 PJ in 2030, from 0 PJ to 610 PJ in 2040 and from 45 to 475 PJ in 2050. Corresponding to the additional demand for renewable fuels, the resulting GHG emission savings range from 0 to 15 Mt. CO_2 in 2030, 0 to 45 Mt. CO_2 in 2040 and 1.5 to 35 Mt. CO_2 in 2050.

5.3.2. *Discussion*

The results for the different regulatory frameworks in 2030 highlight the importance of electrification in the road transport sector to fulfil the legislative GHG reduction goals. While differences between the minimum (S9) and median scenario (S5) remain small related to the year 2030, the maximum scenario S4 already demonstrates significant drivetrain electrification.

For the latter, it can be observed that – with the exception of the national adaptation of the RED II – only the mandatory sub-quotas for advanced biofuels and the blending quota of ReFuelEU Aviation are necessary to meet the obligations, while also exceeding most of the overall targets. In case of the GHG reduction quota in Germany, small amounts of renewable fuels (i.e., biofuels from feedstock listed in RED III Annex IX part B and biofuels from food and feed crops) are necessary on top of the mandatory obligations. This is mainly due to two factors.

- The correction factor is included in the legislation. This factor increases the quota obligation if electricity limits are exceeded, as the surplus GHG emission reduction from electricity use is carried over into future years.
- The system boundary definition. The German GHG quota excludes SAF in aviation entirely; i.e., these renewable fuels cannot be accounted towards the quota – unlike the RED III, which includes aviation in its scope, and also unlike RED II, which generally excludes aviation, but allows aviation fuels to count towards the targets (even with beneficial multiplicators).

The same logic applies to the assessment of different fleet compositions against the KSG. The maximum scenario S4 is sufficient to meet the climate targets without the additional usage of renewable fuels, except for 2050. However, the minimum (S9) and the median scenario (S5) require significant quantities – in addition to the fuels already used to meet the obligations of the RED III. For S5, for example, in addition to the 240 PJ of renewable fuels necessary to meet the GHG reduction quota, an extra 175 PJ of renewable fuels would be necessary in 2030 to meet the KSG target. In this study, there are no assumptions concerning the availability of renewable fuels in general. However, in comparison to today's usage of renewable fuels in Germany (140 to 160 PJ/a), additional (strong) efforts would be necessary to enable the usage of these fuels. If the limitations of the RED concerning certain fuels are transferred to the KSG, an additional obstacle occurs: to meet the KSG targets, nearly solely advanced biofuels or RFNBO could be used (as all other options are already used to their maximum). Today (July 2025), there are no industrial-scale production facilities to meet these demands (even

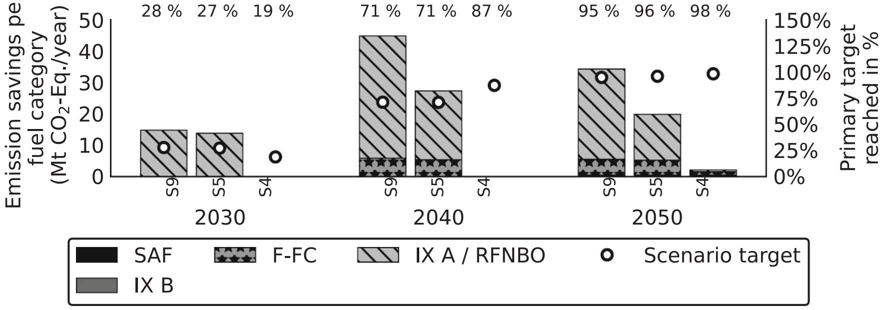

Fig. 14. Emission reduction per fuel category to reach the climate targets of the transport sector according to KSG 2024 based on the framework of the RED III in Germany for the minimum (S9), median (S5) and maximum (S4) scenarios in 2030, 2040 and 2050 (KSG sector targets after 2030 were derived via linear extrapolation from the overall target for the respective years). (RFNBO – renewable fuels of non-biological origin, IX A / B – Biofuels from feedstock listed in RED III Annex IX part A / B, Hydrogen – RFNBO Hydrogen). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

without considering economic implications) [69,75,76].

As mentioned before, the energetic share of the non-road transport sector at the overall energy demand increases over time as the road sector reduces the energy demand. Although energetic quotas are then more strongly affected by the energy demand of these sub-sectors, in terms of GHG emission reductions according to the German KSG, the influence is damped as the KSG excludes international transportation – while the growth in the non-road sectors mainly occurs in the aviation sector, which is largely counted as international aviation.

5.3.3. Placement

In the last years, biofuels have appeared on the market that would generally fit into the category of advanced biofuels – however, these fuels are surrounded by fraud allegations [77,78]. In Germany, there was also fraud detected for another option within the German GHG quota – Upstream-emission-reductions (UER), which were subsequently excluded [79]. It therefore remains to be seen whether and in what quantities these raw materials will continue to be available in the future, or whether completely new production facilities will actually have to be built.

From this, a fast BEV ramp-up seems to be beneficial in multiple ways: As energy demand and GHG emissions decrease, the demand for renewable fuels decreases accordingly – and therefore also the obligations for the mandatory sub-quota for renewable fuels, which is linked to the energy demand of the transport sector. However, the speed and the start of the ramp-up are crucial as well; i.e., as the legal framework not only considers the GHG emission balance for certain years, as, e.g., 2040 or 2050, but also the cumulative GHG emissions. Higher shares of BEV in the vehicle stock can therefore “ease” the pressure not only to roll out more BEV into the market, but also help to manage the simultaneous ramp-up of production facilities for renewable fuels on large scales.

A rapid electrification of the vehicle fleet reduces the long-term need for renewable fuels, thereby lowering the required build-up of production capacities. This helps to avoid stranded investments in fuel production infrastructure that might become underutilized as electrification progresses during the lifetime of these facilities. However, if investors anticipate a fast transition, they might withhold investment in fuel facilities altogether. In this case, renewable fuels could be lacking in the short term, when electrification alone is still insufficient to meet climate targets.

Finally, when comparing the different regulatory frameworks, a fundamental challenge becomes evident: due to varying methodologies and system boundaries, translating one regime into another is highly complex – particularly from the perspective of legislators designing frameworks for the period after 2030 (see also Annex A.2).

The analysis shows that different BEV ramp-up trajectories would require significantly different target levels within the different regulatory frameworks and also to meet overarching targets. This becomes clear in the case of a GHG quota: the quota specifies a relative reduction target (e.g., 30%), but is not linked to an absolute amount of GHG emission reductions. As a result, a 30% GHG reduction according to the quota in a fleet with high baseline emissions may fall short of absolute reduction targets (e.g., under the European Green Deal or the German KSG), while the same percentage applied to a largely electrified fleet may even exceed the necessary reductions. In the latter case, this could imply that renewable fuels previously used to meet the quota are no longer necessary within the respective framework; despite their availability, this might offer the opportunity for further GHG emission reductions beyond the regulatory minimum (and by this also reducing cumulative GHG emissions earlier than expected).

This study evaluates the impact of BEV ramp-up scenarios within the boundaries of the existing regulatory frameworks. As stated in the assumptions, differences between ramp-up scenarios do not affect electricity supply, i.e. neither changes in generation capacity nor corresponding grid emission factors are considered. This reflects the regulatory treatment of electricity use in transport, where emissions are either not attributed to the transport sector at all (KSG) or are accounted for using average values, such as average grid emission factors under the German GHG quota or the average share of renewable electricity under RED II/III.

At the same time, literature indicates that real-world charging behaviour may deviate from the implicit assumptions underlying these average-based, ex-ante defined approaches. Empirical studies show that BEV charging frequently occurs during evening and night-time hours, often coinciding with periods of higher system load and, in several regions, higher marginal emission intensities than suggested by annual averages. [80–82] However, the same body of literature also shows that – with appropriate flanking measures such as pricing schemes, smart charging, and other policy instruments – charging behaviour can be influenced in a way that mitigates these adverse impacts and enable beneficial interactions with the electricity sector, including reduced grid strain, peak demand, and renewable curtailment. [83–85].

6. Conclusion

This study quantifies how varying ramp-up scenarios for battery electric vehicles in the passenger and commercial vehicle segments influence the energy demand of the road transport sector in Germany. These different ramp-up trajectories result in substantial variations in renewable fuel demand and the subsequent GHG emission reduction – both with respect to compliance with the RED II/III and national GHG reduction quota, and with regard to absolute GHG emission reductions required under the German Climate Change Act.

- The analysis of the existing legislative frameworks highlights that these regulations are currently not fully aligned with the modelled expectations for the future (BEV) development in road transport. Moreover, the different accounting methods and system boundaries of the respective frameworks hinder the transferability between the frameworks and, in general, long-term orientation to ensure that the overall targets of the German KSG are met, particularly with regard to increasing amounts of electricity that are balanced within the transport sector.

  As the frameworks of the RED and also the German GHG quota define the reduction target in relation to the reference emissions of the respective year, the achievement of an absolute emission reduction goal of the KSG is not guaranteed, especially against the background of the expected changes in the quantity and composition of the energy demand in the transport sector.
- Another key finding is the high variability of the demand for renewable fuels and the respective reduction of GHG emissions connected to their usage, which is closely linked to the speed of the BEV ramp-up and the achievable overall market share. Even the median scenario S5 shows a substantial demand for advanced biofuels and/or RFNBO, which significantly exceeds the current usage of renewable fuels in general in Germany. This implies an urgent need for expansion of production capacities and raises concerns about the (long-term) availability of the respective sustainable feedstocks. Accelerated BEV ramp-ups prevent transitional spikes in renewable fuel demand that would later decline as BEV adoption accelerates – thereby reducing the risk of stranded production capacities and weak investment incentives due to a short-lived market demand.
- Furthermore, both the RED III and the German GHG quota require the use of advanced biofuels and/or RFNBO, which exceed the minimum quotas for the respective fuels, for the considered ramp-up scenarios. In addition to that, more renewable fuels of these categories may be necessary to achieve the KSG targets. This causes uncertainty for investors and producers, as the required quantities are also sensitive to the actual BEV market penetration achieved.

In summary, this study investigated the interaction between different BEV ramp-up scenarios and the regulatory framework in the German transport sector, focusing on the RED II/III, ReFuelEU Aviation, and the KSG. By applying market diffusion models based on a range of literature-based assumptions, it was possible to quantify how fleet developments translate into energy demand, renewable fuel demand and the corresponding GHG emission reductions over time. The findings show that the resulting energy demand and GHG emission reductions are highly sensitive to both the speed of electrification and the methodology of the regulatory frameworks, particularly in terms of quota-based versus absolute emission targets.

Future work could refine the modelling of fleet composition and turnover dynamics and further explore the interdependencies of the legal frameworks. This would allow for a more accurate assessment of transitional effects, timing mismatches, and potential compliance gaps in achieving national and European climate targets. Also, modal shifts should be investigated in more detail.

CRediT authorship contribution statement

Philipp Anstett: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Michael Schulthoff:** Writing – review & editing, Validation, Methodology, Formal analysis. **Martin Kaltschmitt:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Appendix

A.1. Annex

A.1.1. Excursus: Effect of multiplicators within the regulatory frameworks

In the regulatory frameworks of the RED II/III and the German GHG quota, multiplicators can be used within the respective methodology. These multiplicators are utilized as an incentive for certain options of renewable fuels. However, by using multiplicators, the calculated emission reductions or shares of renewable energies within the regulatory framework differ from "reality" and also their proportionality with regards to options without beneficial multiplicators.

Exemplary, the RFNBO sub-quota of the RED III is based on the final energy demand of the whole transport sector and is set to 1% in 2030, i.e., 21 PJ for scenario S5 (Fig. 15). As assumed, the share of RFNBO SAF in compliance with the ReFuelEU Aviation targets amounts to 5.3 PJ in 2030 (i.e., 1.1% of the kerosene used). Applying the respective multiplicators of the RED III, once for the RFNBO category (2×) and once for the usage of RFNBO in aviation (1.5×), this can be accounted as 15.9 PJ, leaving 5.3 PJ of the sub-quota open. As the multiplicator for RFNBO can be used regardless of the sub-sector, the additionally necessary fuel can be calculated to a maximum of further 2.6 PJ in order to meet the quota of 21 PJ in total.

The same is true for the accounting of RFNBO within the RED III target for the share of renewable energies and also the German GHG quota, which also uses multiplicators. In case of the RED III, the physically used fuel of 7.9 PJ would be counted as 21 PJ for the calculation of the target, while only 7.9 PJ of fossil fuel actually have been substituted. Subsequently, the "real world" emission reduction is also only based on 7.9 PJ of RFNBO.

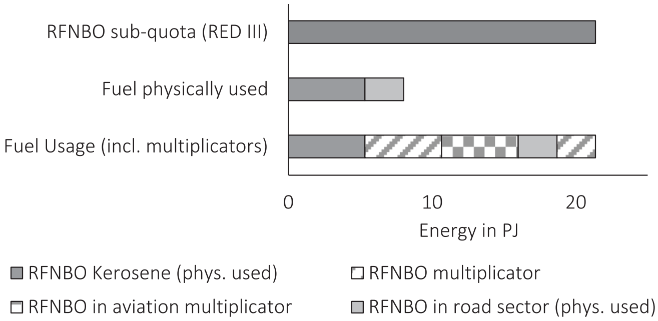

Fig. 15. Exemplary usage of multiplicators within the mandatory sub-quota of the RED III for the median scenario S5 in 2030. (RFNBO – Renewable fuel of non-biological origin). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A.2. Exemplary translation between the different frameworks

The results presented in section 5.3 showed differences between the different frameworks of the RED, the German GHG quota as well as the German KSG. Based on the median scenario for the year 2030 and using the RED III GHG quota as baseline, Table 6 gives an exemplary overview, how the identical use of renewable fuels translates into the metrics of the other frameworks. I.e., according to the baseline, the renewable fuel usage is designed to fulfil the target of 14.5% GHG quota in 2030 as given in the RED III.

The results for the RED III GHG quota, if translated (column "Calculated"), exceed the alternative target of the RED III, the share of renewable energies in the transport sector. For the German GHG quota, this fuel mix would translate to 23.5%, missing the 2030 target of 25% according to the German quota. This is mainly due to the system boundaries used in the frameworks, i.e., the exclusion of the fuels used in aviation according to ReFuelEU Aviation.

As discussed in section 5.3, if evaluated against the German KSG, the fuel mix according to the RED III GHG quota is insufficient and translates into 127 Mt. of residual CO_2 emissions in 2030 in the transport sector – exceeding the target of 82 Mt. In order to stay within the emission budget, a total usage of renewable fuels of 405 PJ or respectively a RED III GHG quota of 27% is necessary (column "Necessary"). As can be seen, for the other frameworks also significantly higher targets would be necessary to ensure to reach the target in the metrics of the KSG.

Table 6
Exemplary overview of differences between regulatory frameworks of the RED III, the German GHG quota and the KSG for the median scenario S5 in the year 2030.

	Calculated	Target	Necessary	Unit
RED III GHG quota	14.5%	14.5%	27.2%	–
Renewable fuels in total	250		405	PJ
Translated into metric of				
Nat. GHG quota	23.5%	25.0%	38.3%	–
RED III renewable share	31.9%	29.0%	59.2%	–
Emissions according to KSG	127	82	82	Mt CO_2 Emissions
Key data for S5 (2030):				
Total energy demand	2120			PJ
Energy demand in road transport	1530			PJ
Electricity used in road transport	75			PJ
Energy demand in non-road transport	590			PJ

A.3. Sensitivity for effect of electricity consumption in PHEV

Besides BEV, the influence of PHEV in the vehicle fleet is publicly discussed – especially the electric driving share [74]. In order to test the robustness of the presented results, the influence of a varying electric driving share on the overall demand for renewable fuels is determined (Fig. 16). As the overall specific energy demand of the PHEV (Ev_{PHEV}) is affected, the fuel consumption (i.e., the liquid fuel without electricity) must be adapted according to (Eq. 11) – (Eq. 13), whereby

- Ev is the specific energy demand (index: Fuel – Energy provided by liquid fuel, Electricity – Energy provided by externally charged electricity),
- τ is the ratio of the specific energy demand of an ICEV and a BEV,
- s is the electric driving share,
- index: 0 – based on original input data before adapting the electric driving share.

$$Ev_{PHEV} = Ev_{Fuel} + Ev_{Electricity} \tag{11}$$

$$Ev_{Fuel} = Ev_{Fuel,0} + \left(Ev_{Electricity,0} - Ev_{Electricity}\right)\tau \tag{12}$$

$$Ev_{Electricity} = \frac{s\, Ev_{Electricity,0}(1 + (\tau - 1)s_0\,)}{1 - s\,(1 - \tau)} \tag{13}$$

It can be observed that the total demand for renewable fuels varies between 400 PJ at an electric driving share of 45% and 430 PJ at a share of 5% (compared to 405 PJ in the reference without adapting the electric driving share based on [21] in order to fulfil the KSG targets in 2030.

Within the scenario framework applied in this study, the overall impact of PHEV on long-term energy demand remains limited. In most scenarios, BEV become the dominant drivetrain over time, while also leading first to a phase-out of ICEV and subsequently to a declining relevance of PHEV in terms of total energy demand towards 2050. Moreover, the assumption of no new ICEV from 2035 onwards implies that the number of PHEV in the vehicle stock does not increase beyond this point. In addition, the developed scenarios already require high net growth rates of BEV compared to current new registrations in Germany (i.e., excluding decommissioned vehicles; see section 5.1.2 and Fig. 8).

Overall, while the electric driving share of PHEV does affect renewable fuel demand, the magnitude of this effect remains moderate within the context of the presented results. However, in scenarios with higher PHEV shares, the assumed real-world electric driving share becomes increasingly relevant, as overestimating this parameter may lead to a systematic underestimation of fuel demand and associated GHG emissions [74]. Given the limited empirical evidence on real-world electric driving behaviour of PHEV and the lack of effective policy measures to ensure high electric driving shares, this constitutes an additional source of uncertainty for emission accounting and climate target compliance. [74].

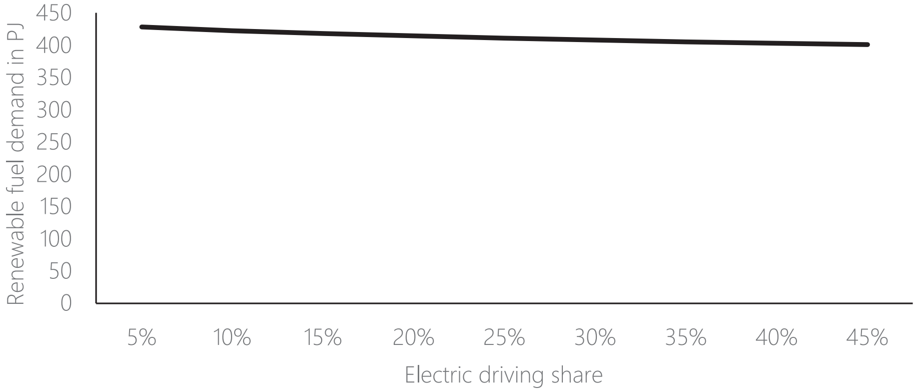

Fig. 16. Change of total demand for renewable fuels to reach the KSG targets in 2030 for the median scenario S5 in dependence of the electric driving share of PHEV. (PHEV – Plug-In hybrid vehicle).

A.3.1. Additional input parameters and assumptions

Table 7
Sampling points and assumed maximum market potential as parameter input for the diffusion models for passenger vehicles. (Data based on [20–25].

Scenario	2030	2040	2045	2050	Market potential (in 10^6 vehicles)
S1				100%	49.1
S2	16%	30%	65%	100%	49.1
S3	18%	55%	76%	100%	49.1
S4	29%	80%	86%	100%	49.1
S5	16%	30%	65%	100%	41.7
S6	18%	55%	76%	100%	41.7
S7	29%	80%	86%	100%	41.7
S8	16%	30%	65%	100%	34.4
S9	18%	55%	76%	100%	34.4
S10	29%	80%	86%	100%	34.4

Table 8
Sampling points and assumed maximum market potential as parameter input for the diffusion models for light- and heavy-duty vehicles. (Data based on [20–25].

Scenario	2030	2040	2045	2050	Market potential (in 10^6 vehicles)
S1				100%	3.3
S2	9%	30%	37%	100%	3.3
S3	19%	60%	85%	100%	3.3
S4	33%	90%	98%	100%	3.3
S5	9%	30%	37%	100%	2.8
S6	19%	60%	85%	100%	2.8
S7	33%	90%	98%	100%	2.8
S8	9%	30%	37%	100%	2.3
S9	19%	60%	85%	100%	2.3
S10	33%	90%	98%	100%	2.3

Table 9
Assumed emission factors for the RED III GHG quota (* from 2031 onwards, the reference value of electricity is set to 183 kg CO_2/GJ by the RED) (** Reference emissions according to [44]) (RFNBO – Renewable fuels of non-biological origin, F-FC – Biofuels from food and feed crops, IX A / B – Biofuels from feedstock listed in RED III Annex IX part A / B, Hydrogen – RFNBO Hydrogen).

Sector	Fuel	Emission factor (kg CO_2/GJ)	Reference value (kg CO_2/GJ))**	Source
Road	Gasoline	93.3	94.0	[63]
	Diesel	95.1	94.0	[63]
	Methane	94.1	94.0	[63]
	Electricity (only renewable part)	0.0	94.0 / 183*	[44]
	Hydrogen	94.1	94.0	[63]
	IX A Methane min	−18.7	94.0	[6]
	IX A Ethanol min	8.3	94.0	[6]
	IX A BtL Gasoline min	8.3	94.0	[6]
	IX A BtL Diesel min	8.7	94.0	[6]
	RFNBO Hydrogen min	9.1	94.0	[63]
	RFNBO Gasoline min	12.0	94.0	[86]
	RFNBO Diesel min	12.0	94.0	[86]
	RFNBO Methane min	12.0	94.0	[86]
	IX B FAME	8.5	94.0	[6]
	IX B HVO	7.6	94.0	[6]
	F-FC Methane	15.9	94.0	[6]
	F-FC FAME	15.8	94.0	[6]
	F-FC Ethanol	9.6	94.0	[6]
	F-FC HVO	14.5	94.0	[6]
	RFNBO Hydrogen in Refineries	9.1	94.0	[6]
	RFNBO Hydrogen	9.1	94.0	[6]
	IX A Methane	−18.7	94.0	[6]
	IX A Ethanol	8.3	94.0	[6]
	IX A BtL Gasoline	8.3	94.0	[6]
	IX A BtL Diesel	8.7	94.0	[6]
	RFNBO Gasoline	12.0	94.0	[86]
	RFNBO Diesel	12.0	94.0	[86]
	RFNBO Methane	12.0	94.0	[86]
Rail	Electricity (only renewable part)	0.0	94.0 / 183*	[44]
	Hydrogen	94.1	94.0	[63]
	Diesel	95.1	94.0	[63]

(continued on next page)

Table 9 (*continued*)

Sector	Fuel	Emission factor (kg CO_2/GJ)	Reference value (kg CO_2/GJ))**	Source
	F-FC FAME	15.8	94.0	[6]
	F-FC HVO	14.5	94.0	[6]
	IX B FAME	8.5	94.0	[6]
	IX B HVO	7.6	94.0	[6]
	IX A BtL Diesel	8.7	94.0	[6]
	RFNBO Hydrogen	9.1	94.0	[6]
	RFNBO Diesel	12.0	94.0	[86]
Shipping	Diesel	95.1	94.0	[63]
	Hydrogen	94.1	94.0	[63]
	F-FC Diesel	15.8	94.0	[63]
	IX B Diesel	7.6	94.0	[6]
	IX A BtL Diesel	8.7	94.0	[6]
	IX A Methane	−18.7	94.0	[6]
	RFNBO Diesel	12.0	94.0	[86]
	RFNBO Hydrogen	9.1	94.0	[6]
Aviation	Kerosene	95.1	94.0	[63]
	IX B Kerosene	7.6	94.0	[6]
	IX A Kerosene	8.7	94.0	[6]
	RFNBO Kerosene	12.0	94.0	[86]
	F-FC Kerosene	14.5	94.0	[6]
Maritime	Diesel	95.1	94.0	[63]
	Methane	94.1	94.0	[63]
	F-FC FAME	15.8	94.0	[6]
	F-FC HVO	14.5	94.0	[6]
	F-FC Methane	15.9	94.0	[6]
	IX B FAME	8.5	94.0	[6]
	IX B HVO	7.6	94.0	[6]
	IX A BtL Diesel	8.7	94.0	[6]
	IX A Methane	−18.7	94.0	[6]
	RFNBO Diesel	12.0	94.0	[86]
	RFNBO Methane	12.0	94.0	[86]

Table 10

Assumed emission factors for the German GHG quota. (RFNBO – Renewable fuels of non-biological origin, F-FC – Biofuels from food and feed crops, IX A / B – Biofuels from feedstock listed in RED III Annex IX part A / B, Hydrogen – RFNBO Hydrogen).

Sector	Fuel	Emission factor (kg CO_2/GJ)	Reference value (kg CO_2/GJ))	Source
Road	Gasoline	93,3	94.1	[63]
	Diesel	95,1	94.1	[63]
	Methane	94,1	94.1	[63]
	Electricity	28,9	94.1	[87]
	Hydrogen	37,6	94.1	[63]
	IX A Methane min	−18,7	94.1	[6]
	IX A Ethanol min	8,3	94.1	[6]
	IX A BtL Gasoline min	8,3	94.1	[6]
	IX A BtL Diesel min	8,7	94.1	[6]
	RFNBO Hydrogen min	3,6	94.1	[6]
	RFNBO Gasoline min	12,0	94.1	[86]
	RFNBO Diesel min	12,0	94.1	[86]
	RFNBO Methane min	12,0	94.1	[86]
	IX B FAME	8,5	94.1	[6]
	IX B HVO	7,6	94.1	[6]
	F-FC Methane	15,9	94.1	[6]
	F-FC FAME	15,8	94.1	[6]
	F-FC Ethanol	9,6	94.1	[6]
	F-FC HVO	14,5	94.1	[6]
	RFNBO Hydrogen in Refineries	9,1	94.1	[6]
	RFNBO Hydrogen	3,6	94.1	[6]
	IX A Methane	−18,7	94.1	[6]
	IX A Ethanol	8,3	94.1	[6]
	IX A BtL Gasoline	8,3	94.1	[6]
	IX A BtL Diesel	8,7	94.1	[6]
	RFNBO Gasoline	12,0	94.1	[86]
	RFNBO Diesel	12,0	94.1	[86]
	RFNBO Methane	12,0	94.1	[86]
Rail	Electricity	72,2	94.1	[87]
	Hydrogen	37,6	94.1	[63]
	Diesel	95,1	94.1	[63]
	F-FC FAME	15,8	94.1	[6]
	F-FC HVO	14,5	94.1	[6]

(*continued on next page*)

Table 10 (*continued*)

Sector	Fuel	Emission factor (kg CO_2/GJ)	Reference value (kg CO_2/GJ))	Source
	IX B FAME	8,5	94.1	[6]
	IX B HVO	7,6	94.1	[6]
	IX A BtL Diesel	8,7	94.1	[6]
	RFNBO Hydrogen	3,6	94.1	[6]
	RFNBO Diesel	12,0	94.1	[86]
Shipping	Diesel	94,1	94.1	[63]
	Hydrogen	37,6	94.1	[63]
	F-FC Diesel	15,8	94.1	[6]
	IX B Diesel	8,5	94.1	[6]
	IX A BtL Diesel	8,7	94.1	[6]
	IX A Methane	−18,7	94.1	[6]
	RFNBO Diesel	12,0	94.1	[86]
	RFNBO Hydrogen	3,6	94.1	[6]
Aviation	Kerosene	94,1	94.1	[63]
	IX B Kerosene	7,6	94.1	[6]
	IX A Kerosene	8,3	94.1	[6]
	RFNBO Kerosene	12,0	94.1	[86]
	F-FC Kerosene	14,5	94.1	[6]
Maritime	Diesel	94,1	94.1	[63]
	Methane	94,1	94.1	[63]
	F-FC FAME	15,8	94.1	[6]
	F-FC HVO	14,5	94.1	[6]
	F-FC Methane	15,9	94.1	[6]
	IX B FAME	8,5	94.1	[6]
	IX B HVO	7,6	94.1	[6]
	IX A BtL Diesel	8,7	94.1	[6]
	IX A Methane	−18,7	94.1	[6]
	RFNBO Diesel	12,0	94.1	[86]
	RFNBO Methane	12,0	94.1	[86]

Table 11
Assumed mileage for different segments according to (Deutsches Zentrum für Luft- und Raumfahrt (DLR) & Deutsches Institut für Wirtschaftsforschung Berlin e. V. (DIW Berlin) 2024[56]. (Commercial vehicle categories weighted according to vehicle number in fleet stock) (LDV – Low-duty vehicle, MDV – Medium-duty vehicle, HDV – Heavy-duty vehicle.

Segment		Mileage (thousand vehicle-km/a)
Passenger vehicles	Diesel	17.7
	Gasoline	9.7
	Alternative drivetrain	16.2
Commercial vehicles	LDV (< 3.5 t)	18.9
	MDV (3.5–7.5 t)	15.5
	HDV (7.5–12 t)	33.5
	HDV (> 12 t)	89.4
	Busses	52.2

Data availability

Data will be made available on request.

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