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Land transport development in three integrated scenarios for Germany – Technology options, energy demand and emissions

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A R T I C L E I N F O

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A B S T R A C T

Today, transportation contributes significantly to greenhouse gas emissions and air pollution. However, new technologies are emerging and existing technologies are being further improved. This article presents the results of a comprehensive study on the development of drive-trains, resulting electricity and fuel consumption as well as emissions of CO_2 and selected air pollutants in land transport in Germany. This includes a quantitative assessment of technological potentials and of resulting energy consumption and emissions. The scenario building followed an explorative approach. Only the scenario depicting a consistent transition towards electrified mobility and regulated emissions from the energy system leads to a significant reduction in transport related CO_2 emissions. Yet, the analysis shows that it is unlikely that the German emission reduction target in 2030 for the transport sector will be met. Nevertheless, the integrated scenario analysis demonstrates that only a joint de-carbonization of both transport and electricity systems lead to a significant reduction of emissions.

1. Introduction and objectives

Land-based transportation is still largely fossil fuel driven and consequently causes high emissions of greenhouse gases, above all carbon dioxide (CO_2), and air pollutants. Even in highly developed countries with advanced environmental targets and standards such as Germany there is still a high level of urban air pollution from both passenger and freight transportation. Driven by politically set incentives and constraints as well as highly innovative actors, new vehicle concepts are emerging and existing drivetrains are being further improved regarding efficiency and emissions. Scenario analyses help to assess the role and possible effects of such future technologies in a systematic and transparent way. Especially the quantification of direct emissions of air pollutants, however, needs to be expanded beyond tailpipe emissions from vehicles and emissions from energy supply need to be included. This is important particularly with regard to the generation of electricity, since electrifying transport is a key strategy of energy transition (e.g., McLaren et al. 2016; Zimmer et al. 2016). But also a large-scale generation of synthetic fuels such as hydrogen or synthetic methane (power-to-gas – PtG) and synthetic liquid hydrocarbons (power-to-liquid – PtL) would require large amounts of additional renewable electricity (Michalski et al. 2017; Dietrich et al., 2018). This energy requires additionally installed capacities in Germany or in future supply regions such as countries within the sunbelt of the earth (see e.g. Pregger et al. 2020).

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Long term scenario studies which consider the whole energy system usually take into account this relation between energy supply of future transportation and required additional generation (see e.g., studies with a focus on Germany such as WWF 2009; Pregger et al. 2013; Schlesinger et al. 2014; Ökoinstitut and ISI 2015). However, these studies contain usually rather simple analyses of the transport sector based on assumptions, narratives and extrapolations of current trends. On the other hand, explorative in-depth studies on future mobility considering interrelations between demand drivers, costs and effects, as well as travel behavior and car use, largely ignore the requirements on the energy system and related emissions that have to be assigned to the transport sector (e.g. ITF 2017; Schönduwe and Lennert 2016). Existing transport studies for Germany considering the energy supply for transportation in an integrative way are above all the RENEWBILITY studies (BMU 2009; UBA 2013; Zimmer et al. 2016). Although energy demand and generation was integrated into the assessment of different transportation pathways air pollution emissions were not considered in their analyses. The current guideline methods for determining and evaluating emissions from the transport sector usually neglect the upstream emissions, particularly of air pollutants, from the electricity generation of vehicles with electric drive-trains (see e.g. EMEP/EEA 2019). This is done to strictly separate the sectors in order to avoid double counting for emission reporting. For prospective scenario analyses, however, this leads to an increasingly incomplete picture of the environmental effects of mobility. There are already many studies in the context of well-to-wheel and life cycle assessment that link the energy and transport sectors in order to obtain a suitable basis for comparing vehicle concepts. For example Wu et al. (2012), Bauer et al. (2015), Moro and Lonza (2018) and Ehrenberger et al. (2019) calculated upstream GHG emissions of electric vehicles including scenarios for electricity generation. The results clearly show the importance of these assumptions for the ecological assessment of electric vehicles and in particular the strong effect of GHG emissions from the use phase of the vehicles in the case of fossil power generation. Main focus of such analyses is the influence of an increasing share of electric vehicles on the energy system and the assessment of a single transport mode, mostly passenger cars. Regarding the CO_2 benefits of electric vehicles, different methodological approaches can lead to conflicting results (Jochem et al., 2015). Nordelöf et al. (2014) and Marmiroli et al. (2018) noted that most of the articles conclude that electricity source is an important driver of CO_2 emissions of electric vehicles, but other studies do not support this conclusion, leading to a lack of a coherent message on environmental impacts of electrified transport modes. With respect to air pollutants, the uncertainties of prospective evaluations are even higher, as air pollutant emissions are largely a result of environmental regulations for thermal energy conversion and assumptions on the penetration of technologies without direct emissions such as PV and wind power plants.

Scenario-based integrated analyses of the energy and transport sector are found, for example, in Lott et al. (2017) and Schmid et al. (2019) with the aim of examining the influence of costs caused by air pollutant emissions on the determination of cost-minimized energy systems. The results confirm a significant impact and show significant air pollution co-benefits in scenarios that meet the objectives of the Paris Agreement. Therefore, it is concluded that an integrated assessment of the reduction of GHG and air pollutants is important. However, the results are not explicitly evaluated in these and similar studies with regard to direct and indirect emissions from the transport sector. A recent *meta*-analysis of new passenger car registration scenarios for Europe and the US points out that data points in terms of range of market shares of the electrified powertrains are comparable for moderate scenarios. Progressive scenarios show a large range of similar market shares and especially spread from 2030 onwards. This is mainly due to different political and technical parameters (van den Adel and Klötzke, 2018) and complicates the comparability of different scenario approaches.

Another aspect of existing scenario studies is the dominance of goal oriented scenarios. Several examples (WWF 2009; Schönduwe and Lennert 2016; Zimmer et al. 2016; Gerbert et al., 2018) of transitional pathways are explored to achieve GHG reduction targets in Germany. For example Schanes et al. (2019), IEA (2017), van den Adel et al. (2018) and Pagenkopf et al. (2019) developed back-casting narratives to achieve resource efficiency and low carbon futures on European and global level respectively. Within goal oriented scenarios, aspects of plausibility and consistency are often neglected in order to create narratives that lead to a desired end-point. For the European car market, van den Adel et al. (2018) show that the number of combustion engine vehicles would have to decrease significantly in a 1.5 °C scenario the gap has to be filled by zero emission vehicles. This would require a tremendous change in the automotive sector with a sharp growth in production and development capacities of battery and fuel cell electric vehicles until 2030. In contrast to that approach, the aim of our explorative transport scenario approach is to focus on options for action within the jurisdiction of national governments and derive consistent and plausible context storylines with rather open end-points.

Within the framework of the project *Transport and the Environment* (VEU) (Henning et al., 2015), twelve institutes engaged in creating such explorative bottom-up scenarios for Germany in 2040: a *Reference* scenario and the scenarios *Free Play* and *Regulated Shift*. From a story and simulation approach, input parameters for a network of models were derived (see supplemental material of Winkler and Mocanu (2020,)). By taking a systems approach with interdependent effects on different levels, this work addresses significant gaps in prospective emission estimation of greenhouse gases and air pollutants from the German mobility system and its future cars and vehicle fleets. The explorative character of our scenarios enables us to assess possible pathways of the German land transport system in a bottom-up modelling approach. Combining specific models for the different transport modes gives an answer to the question whether the assumed measure are sufficient to reach the national emission targets. Our scenario analysis should be seen as complementary to existing studies, and span a substantiated possibility space for the transport sector in Germany.

2. Methodology and data sources

2.1. Scenario overview and overall modelling approach

The goal of the scenario analysis is to develop three plausible and consistent pathways of the transportation system in Germany. The scenarios *Reference*, *Free Play* and *Regulated Shift* are explorative scenarios that focus on micro aspects, including regulations, financial measures, investments and behavior. All three scenarios have similar population and wealth trajectories in order to highlight the effects of changes in micro aspects. The three different scenarios for Germany (see Table 1) were determined using a story and simulation approach and a Cross-Impact-Balancing (CIB) method (Weimer-Jehle 2006). In our approach of explorative scenario development for the transport sector we focused on micro aspects, which can be influenced by local or regional policy decisions or through citizen initiatives. At the same time, we fixed the framing conditions, i.e. the paths of macro aspects such as GDP, crude oil prices and overall population development. The final combinations of scenario parameter were tested with the CIB approach. The results of CIB are combinations of parameter developments that are internally consistent, meaning that their interdependencies do not contradict each other. By choosing a middle of the road scenario parameter combination and two most diverging combinations from the list, we created the three context scenarios presented here. For the detailed methodological approach and a full list of scenario-based model input parameters please refer to the supplemental material of Winkler and Mocanu (2020).

Data for transport energy consumption and emissions for the base year 2010 are statistical data for Germany (BMVI 2014; IFEU 2012; Knörr et al. 2016; Keller et al. 2017). In a first step, we used the scenario framework to model the number of vehicles in Germany by taking German cohort effects and trends in car ownership into account. Based on empirical car ownership rates for specific cohorts were analyzed and projected the future number of cars using a Gompertz function. For the scenarios *Free Play* and *Regulated Shift* we translated behavior changes (e.g. people age 18–40, two + households, have 10% less cars in Regulated Shift compared to Reference. For additional assumption see supplemental material) consistent with the scenario storylines and then incorporated the resulting saturation of car ownerships into the Gompertz function. The overall car development was matched with a stock turnover model to derive the year by year new registrations, size distribution, segment specific survival and mileage degression curves and total number of cars (after peaking at 46 million passenger cars, it declines to 43 million in the *Reference* scenario 2040, 45 million in the *Free Play* scenario and 35 million in the *Regulated Shift* scenario). The vehicle stock of LDV and HDV is extrapolated based on the past performance.

Since new propulsion technologies, particularly electric drives are swiftly appearing, we integrated hybrid technologies, battery-electric and fuel cell technologies in our analysis. In the case of passenger cars, applying the detailed bottom-up market simulation model VECTOR21 resulted in consistent pathways of the vehicle fleets (Seum et al. 2020). The projection of the commercial vehicle market is modelled by applying different assumptions on the total cost of ownership. For the past years, our models use historical data of the German Federal motor transport authority, but at the time of calculation, only data until 2017 has been available. The simulated fleet compositions were translated via endogenously calculated specific fuel consumptions into detailed energy consumptions of the entire fleet up to the scenario year 2040. The development pathways for bus and rail transportation are derived from results from transport demand in combination with improved performance and changes in passenger utilization of the transport modes. The development of transportation activities and resulting vehicle mileages by mode were modelled with the DEMO transport demand model (Winkler and Mocanu 2017). The detailed methodology on the fleet development and travel demand is described in Section 2.2.

In a second step, we modified and enhanced existing emission factors for vehicles of all transport modes (see Section 2.3). Furthermore, for accounting of emissions from externally chargeable vehicles and vehicles using overhead lines, as well as for the electrified rail transport, emissions from electricity generation were quantified using defined scenarios of the German energy system, consistent with the VEU scenario storylines. Therefore we extended the transport storylines onto the complete energy system on the basis of plausible assumptions about the development of the German energy system until 2050. The three different storylines about main drivers defined in the frame of the VEU project were translated into long-term pathways for the entire energy system with a focus on the future power system (see Section 2.4).

To ensure the consistency of our model approach, we based the integrated land transport assessment on a model coupling as

Table 1
Storylines and description of model input parameter for selected aspects in the three VEU scenarios.

	Reference	**Free Play**	**Regulated Shift**
Storyline	Represents a continuation of currently existing trends, but also moderate improvements regarding the implementation of new technologies and the use of renewable energies (RE) in the transport sector.	Society follows a liberal market-economic logic. The state in this scenario takes a step back, trying to avoid hampering developments through an overburden of regulations.	Society implements more stringent regulations, combined with investments in infrastructure for public transport and financial instruments to foster the development of certain clean technologies.
CO_2 target values for new passenger cars	Moderately tightened (65 g CO_2/km in 2040)	Fixed at 2020 values (95 g CO_2/km in 2040)	Stringently tightened (45 g CO_2/km in 2040)
Fiscal measures for passenger vehicles	Continuation of current taxation schemes; no additional tax on H_2 and electricity	Harmonization of all fuel tax including taxation of H_2 and electricity for mobility	Harmonization and increase of diesel and gasoline fuel taxes; no tax on H2 and electricity
Financial provisions for the public transport sector (storyline) implemented as changes in the travel time and speed	ravel-time increase in rural, decrease in urban areas; moderate increase passenger utilization	Moderate travel-time increase in short distance and strong increase in long-distance transport; decreasing passenger utilization	Strong decrease travel-time in urban areas; moderate decrease in rural and long distance travel. Strong increase in passenger utilization.
Charging and fuelling infrastructure	75% coverage electric charging, 24% for CNG and 7% for H_2	50% coverage electric charging, 17% for CNG and 7% for H_2	100% coverage electric charging, 35% for CNG and 15% for H_2
Transformation of the energy system	Share of renewable electricity greater than 50%; some smart grid solutions	Share of renewable electricity 40%; centralized system	Share of renewable electricity 78%; decentralized with buffer and storage technologies

presented in Fig. 1. A detailed fleet modeling of the passenger car sector in Germany was carried out with the VECTOR21 model (Mock 2010, Redelbach et al., 2013; Schimeczek, 2015). Transport demand and modal shares were provided by the integrated transport demand model DEMO (Winkler and Mocanu 2017) using the same scenario parameters where applicable. Overall energy demand from the DEMO model for various transport types was then fed into an energy system model for building the complete energy and emission scenarios. This model accounts for the additional energy supply and its effects due to the power and synthetic fuel demand in the German energy system. A detailed description on each modeling approach is presented in the following sections.

2.2. *Simulation of vehicle fleets*

2.2.1. *Passenger cars*

The emissions of future passenger car fleets depend largely on two aspects: the development of the vehicle and engine sizes, and the development of the propulsion technologies, which depends on the market potential of each technology (Seum et al. 2020). Both development pathways are imbedded in the societal context and thus were modified according to the VEU scenario storylines.

The future passenger car and engine size development was based on an analysis of 2008–2015 vehicle registrations, combined with information on engine size developments. In this period, the fastest growing vehicle segment was that of Sport Utility Vehicles, which grew by 26% in stock (KBA 2016). Furthermore, a trend to smaller engines and simultaneously higher engine power can be observed (Fontaras et al. 2017; ICCT 2018). For the projection of future passenger cars, we categorized the vehicles in small (S), medium (M) and large (L) vehicles. For the *Free Play* and *Regulated Shift* scenarios, assumptions were made on the trends towards larger respectively smaller vehicles, and higher power respectively more engine downsizing (Seum et al. 2020).

With regard to the *Reference* scenario as well as with regard to the starting point for conventional gasoline (G) and diesel (D) vehicles, we used the data of the Handbook of Emission Factors for Road Transport (HBEFA v. 3.3). The Handbook differentiates the vehicles by three engine classes ($<$1.4 l, 1.4 $<$ 2.0 l and $\geq$ 2.0 l), gasoline, diesel and gas engines and emission standards (EURO 0–6). It also provides a fleet composition and a vehicle kilometer usage differentiated according to inner urban, extra urban and highway roads. For our analysis, we added vehicles with compressed natural gas (CNG) as fuel, vehicles with hybrid technologies (gasoline full hybrid electric vehicles (G-HEV, diesel full hybrid electric vehicles (D-HEV), gasoline plug-in-hybrid vehicles (PHEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV)). We then formed own, scenario driven vehicle fleet compositions, consistent with the scenario storylines, in order to assess the emission effects.

The vehicle technology scenario model VECTOR21 was used to analyze the market penetration of alternative powertrains under the framework settings of the three scenarios. The model is a hybrid of an agent-based and discrete choice market penetration model that assesses the competition between different powertrain alternatives (Kugler et al., 2017; Schimeczek, 2015). Important drivers are

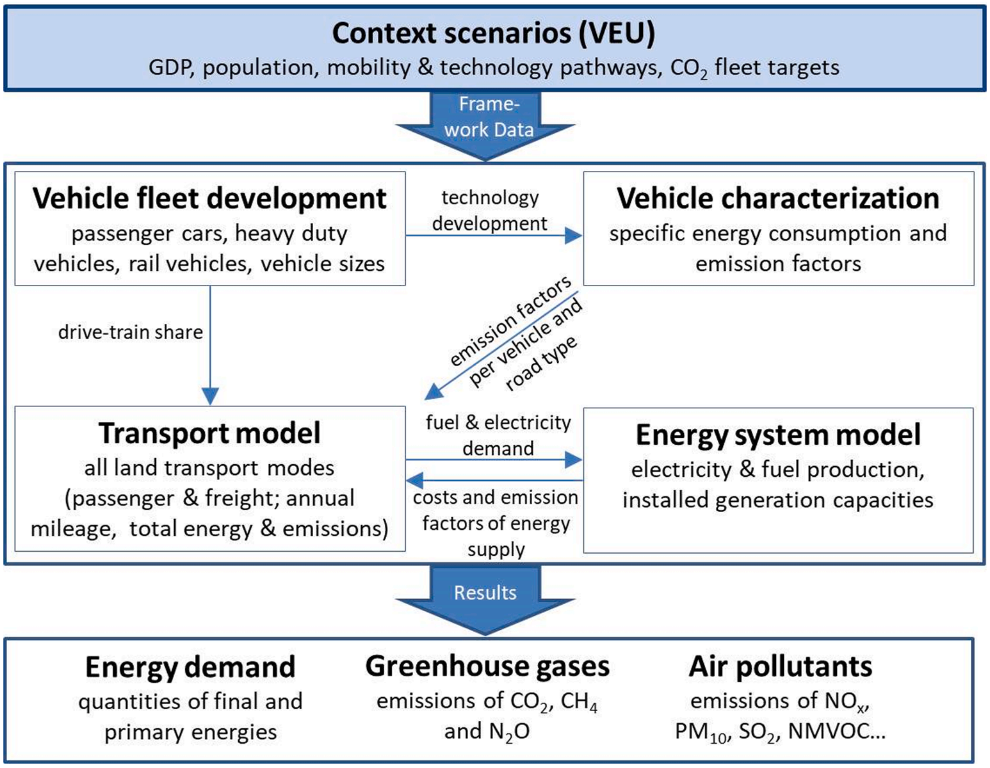

Fig. 1. Model coupling for the integrated assessment of energy and emissions.

hereby the EU CO_2 target values for newly registered passenger cars as average per manufacturer vehicle fleets, the fuel taxation schemes that influence consumer fuel prices and the charging and fueling infrastructure coverage for alternative vehicles (see section 2.2. and Table 1 and Seum et al. 2020 for details). In the VECTOR21 stock module, the fleet renewal is calculated using statistical data on vehicle mileage curves and age distribution per segment size (DLR and Infas, 2010). Survival probabilities are lower with higher annual mileages (as in case of larger vehicles) and range from mean vehicle ages of 15 years (50% survival probability, low annual mileages) to 5 years (50% survival probability, high annual mileages).

2.2.2. Commercial vehicles

The vehicle stock of light commercial (LCV) and heavy goods vehicles (HGV) is extrapolated from the past performance using German vehicle statistics (KBA 2016). It is based on long-term data series of the commercial vehicle stocks and new registered trucks and semitrailer tractors from 1990 onwards. The stocks of five vehicle size classes of categories N1 to N3 are extrapolated until 2040 same for all scenarios (Fig. 2). The stocks of rigid trucks with trailers with a permissible total weight of 40 tons are part of the HGV. They are derived from the stock of heavy trailers and form a 69% share of HGV.

The vehicle fleet of LCV and HGV grew by 800,000 units from 2.6 million in 2010 to 3.4 million in 2040. Within the individual size classes, LCV recorded the highest growth with more than 850,000 vehicles, followed by semitrailer tractors with 20,000 vehicles. The other vehicle classes decline over time.

In order to reduce complexity, the vehicle classes are reduced to two classes. The first class consists of the N1, N2 and the HGVs, driving as rigid trucks without trailers - in the following LCV. The second class - in the following HGV - with a much higher annual mileage is made up of the rigid trucks with trailers and semitrailer tractors and, in the Free Play scenario, the long trucks. The first class group grows from 2.3 million units in 2010 to 3.1 million units in 2040. The second HGV group grows from 308,000 vehicles in 2010 to 332,000 vehicles in 2040. In the Free Play scenario, long trucks with a total length of 25 m and a gross vehicle weight of 40 tons are introduced as an additional vehicle class. They replace and thus reduce tractor units by a ratio of two to three.

The technological development of the powertrain of LCVs and HGVs was projected by applying different assumptions on the total cost of ownership (TCO) including vehicle costs, consumption and maintenance costs as described in Kleiner and Friedrich (2017a) and Kleiner and Friedrich (2017b). For seven reference vehicles in size classes N1 to N3, the vehicle-relevant power unit technologies to be taken into account were defined similar to the passenger car market and their development continued until 2040: vehicles with internal combustion engines using diesel (D) and natural gas (NG), HEVs (in this case both mild hybrid electric and full hybrid electric vehicles, hybrid catenary trucks (HO-truck), PHEVs, BEVs and FCEVs.

In general, the LCV and HGV applied technologies are strongly related to the purchasing and operational costs of those technologies, since market actors have to respect the economic viability of technological solutions. Currently the diesel fuel costs contribute to about one third to the operational costs of road goods transport (Shell 2016). Nearly all heavy trucks today are propelled by diesel engines and only in the LCV segment a 9% share of gasoline and alternative propulsion systems can be observed. Following this mechanism, the LCV and HGV market shares have been derived from the TCO calculation (Florian Kleiner and Friedrich, 2017 a) and internal expert discussion based on the different frameworks of the scenarios.

2.2.3. Rail based public transport and buses

For the public transport, we based our calculation on passenger-kilometer travelled. Therefore, we did not develop a future fleet, but modified the performance figures of today's public transport vehicles. In 2010, the share of diesel propulsion in rail transport was 2% for long-distance trains and 17% for regional trains (IFEU 2012). We assumed that those shares will decline to zero for long-distance trains in 2040 and to 12%, 14% and 5% for regional trains in the *Reference*, *Free Play* and *Regulated Shift* scenarios. Additionally we assumed a 2% and 5% share of fuel cell propelled regional trains in the *Reference* and *Regulated Shift* scenario. For public

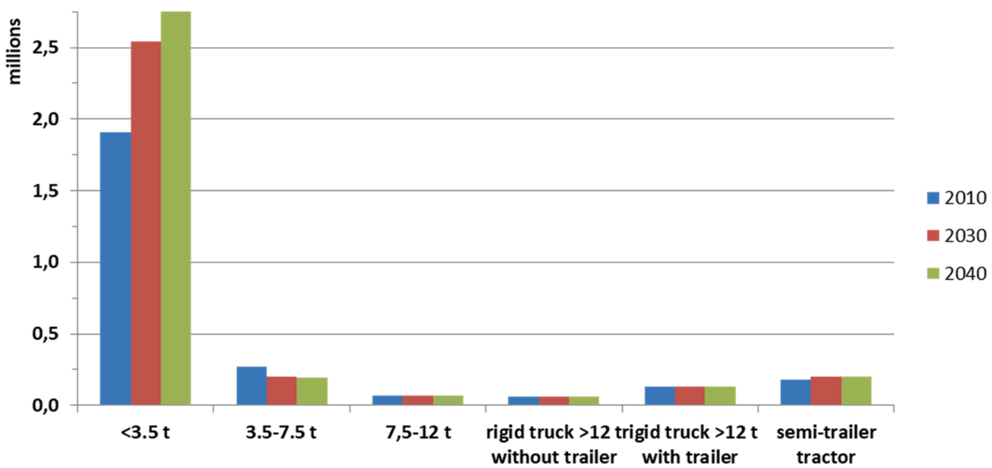

Fig. 2. Development of the number of commercial vehicles up to 2040.

buses, which are 100% diesel driven in 2010, we assumed a share of 5% and 30% propelled by fuel cell technology in 2040 in the *Reference* and *Regulated Shift* scenarios respectively. Our assumptions on fuel cell technologies are based on e-mobil BW (2016).

2.2.4. Rail based freight transport

Comparable to rail-based public transport, rail-based freight transport is calculated based on ton-kilometers and thus no rail fleets were modelled. We assumed that the diesel traction share declines from 3.6% in 2010 (IFEU 2012) to 2% in all scenarios for rail-based freight transport.

2.2.5. Overall travel demand calculations

To conclude the calculation on the road transport sector, transport performance and modal split was modelled with DEMO, a fully synthetic, four-step multimodal travel demand model for Germany (Winkler and Mocanu 2017). The actual figures for travel demand and model split are taken from Winkler and Mocanu (2020) who applied the same scenario settings to the DEMO model. The passenger transport performance over all modes (active modes, passenger car (PC) and public transport (PT)) increases slightly in the *Reference* and *Free Play* scenario and is stagnant in the *Regulated Shift* scenario, despite a slightly declining population. However, the scenario measures that influence the market position of the regional public transit and long distance rail considerably affect the modal use. In particular in *Regulated Shift* a modal shift from PC to PT is observed. PC use declines from 930 to 850 billion passenger kilometer. The PT transport demand increases from 146 billion to 207 billion passenger kilometer. The use of bicycles and walking also show significant increases. A more dramatic picture is seen in freight transport where the demand increases by more than 50% in all scenarios (from 608 billion ton kilometer to around 930 billion) and the share of rail and water transport declines in *Reference* and *Free Play* scenario. Only in *Regulated Shift* freight transport by rail increases with 68% more than road freight transport (Winkler and Mocanu, 2020)). Thus modal shift is a significant mechanism and the transport system is sensitive to certain measures. However, it has to be combined with technological innovation for further emission reductions. In the next section we will discuss our approach to modelling the fleet and emissions progression for the different means of transport.

2.3. Calculation of tailpipe emissions for road passenger and freight transport

In our scenario analysis we combined existing emission factors with emission factors of our own, based on dynamometer tests and literature reviews. For the emissions of conventional technologies (gasoline and diesel), we used the emission factors of the HBEFA database. HBEFA (v3.3) offers a solid base of emission factors for motorcycles, passenger cars (PC), LCV, HGV and buses (BUS) (TU Graz, 2009; Keller et al., 2017; see Table A1).

2.3.1. Passenger cars

In addition to those available categories, we added the emission factors for hybrid and electric vehicles. The derivation of the emission factors is described in Seum et al. (2020). Finally, we made the fleet-composition that determines the emission factors per road category more flexible and deviate from the HBEFA basis. Three different vehicle fleet compositions with regard to size and technology as well as with differentiated use per road category were developed. Our approach to develop the fleet-wide emissions is presented in the next section.

As for air pollutant emissions, in particular CO, NO_x and PM, we expect the emission factors for conventional technologies to decline in the future, due to stricter regulations and controls in the upcoming years. With regard to hybrid technologies, the pollutant emissions depend on the electric range and the share of electric driving per road category. Studies on hybrid electric vehicles (HEV) emissions report possible emission savings of up to 60% for particular pollutants (Fontaras et al. 2008; Alvarez and Weilenmann 2012; Suarez-Bertoa and Astorga 2016). As there are large uncertainties concerning the real reduction potential on the road, a conservative reduction of 10% in addition to the reduction of conventional EURO 6 vehicle has been assumed. Furthermore, a reduction of 10% of emissions in urban areas due to the use of the electric motor for propulsion was assumed for HEV as default. The emission factors of plug-in hybrid electric vehicles (PHEV) are based on own measurements of emissions of a mid-size PHEV on the DLR owned dynamometer (exemplarily described in Kugler et al. 2016). These measurements delivered the emissions for the different road categories and temperatures as well as a utility factor to take into account the different electric driving shares in urban, extra-urban and highway driving situations. The resulting emission factors for the single vehicles types are presented in (Seum et al. 2020). Energy consumption and carbon dioxide emissions were simulated within the VECTOR21 tool using the world harmonized light-duty vehicle test cycle (WLTC). The energy consumption and the CO_2 emissions of future vehicles are calculated based on the technology developments and efficiency improvements defined in the VEU scenarios. For hybrid vehicles, the main influencing aspect for the energy efficiency and the share of fossil driving is the electric range. We applied this range to determine the utility factors for each vehicle. Hybrid vehicles achieve thereby a better fuel efficiency on all roads due to the permanent electric assistance of the hybrid system in addition to portions of pure electric driving in particular on urban roads. As the electric range increases, both fuel consumption and the emissions from fuel combustion decrease to a certain level in the forthcoming years. The finally applied emission factors are aggregated factors for the scenario vehicle stocks per road categories urban, extra-urban and highway on a vehicle kilometer basis. The final scenario emission factors per vehicle type are thus a combination of technological progressions and the change in fleet compositions as described in (Seum et al. 2020).

The market model is further influenced by the European fleet targets. Though this target does not affect the single vehicles, it is an important indicator for the overall technology development and measures need to be taken by the car manufacturers to meet these targets. In our study, we assume a CO_2 fleet target of 65 g/km in 2040 in the *Reference* scenario, 95 g/km in the *Free Play* scenario and

45 g/km in the *Regulated Shift* scenario.

2.3.2. Commercial vehicles

There are several technologies for LCV and HGV vehicles that may enter the market in the future. For LCV vehicles hybridization and electrification can be expected, whereas for HGV compressed and particularly liquefied gas (CNG and LNG) present viable technological options. Furthermore, also for HGV vehicles hybrid electric drives may be implemented in particular for last mile delivery and the full electrification with overhead lines is currently being tested (Shell 2016). Fuel-cell vehicles will likely not be economically competitive in the time horizon until 2040 for LCV and HGV.

For light and heavy commercial vehicles, we used a similar approach and the HBEFA emission factor as a basis. However, we modified the future vehicle fleet composition consistent to the scenario storylines. The energy consumption is simulated assuming an average load factor of 60%.

2.3.3. Rail based transport and buses

A simplified scenario approach was selected for rail-based transport and public transit buses. The base emission factors were taken from the TREMOD model (IFEU 2012), in particular the updated factors for the year 2016 (Knörr et al. 2016). The scenario developments were implemented through assumptions mainly in two areas: firstly increased energy efficiency through technological and operational improvements and secondly the utilization of vehicles (see Table S-2 supplemental material). Energy efficiency may be particularly improved by reducing aerodynamic drag, implementing lightweight materials, improving main and ancillary engines, energy recovery and improving operational services (VDE 2013). The degree to which technological and organizational improvements can be realized was estimated according to the VEU scenario storylines (Table 2).

Apart from energy consumption, the passenger utilization rates of public transport vehicles are the main driver for the overall emission performance of rail-based transport, besides technical and operational improvements. The passenger utilization is defined as the percentage of utilized seat spaces. This utilization is higher in long-distance services compared to urban public transport (IFEU 2011). Utilization factors for the base-year 2010 were derived from figures by the Deutsche Bahn (DB 2011) and the Association of German Transport Companies statistics 2010–2015 (VDV 2011). Changes in passenger utilization are dependent on pricing schemes as well as improvement in comfort and access. We qualitatively assessed the utilization changes of public transport based on base year 2010 utilization rates and target utilization rates for the year 2020 (IFEU 2012). For the following years assumptions were set according to the scenario storylines, e.g. in the *Reference* scenario the trend 2010 to 2020 continues muted with a factor 0.5 and in the *Regulated Shift* scenario the 2010 to 2020 trend is kept stable for inter-city trains and high-speed trains and accelerates with a factor of 2 for regional trains, trams, metro and public buses. For the *Free Play* scenario a reduction of utilization by 1% per year was assumed in the years after 2020 (see Table A2).

In addition to the rail-based public transport, we estimated energy efficiency improvements for diesel driven public buses (Shell 2016) and assumed the introduction of hydrogen fuel-cell buses for the *Reference* and the *Regulated Shift* scenario (Stolzenberg 2017). Energy efficiency improvement ranges from −11% in 2040 in the *Free Play* scenario to −37% in the Regulated Shift scenario.

2.4. Energy scenario modelling

Main input data for the energy scenario development were power, heat and fuels consumptions (including detailed demand information from transportation as result of the calculated transport scenarios) and the shares of electricity generation based on renewable energies (Table 3). The main aim of the scenario building was to derive energy demand and supply balances in line with the socio-economic assumptions and political settings of the three transport scenarios. The energy system model for Germany provides an accounting of complete energy balances and was implemented with the commercial software Mesap/PlaNet (see Schlenzig 1999). Mesap-based energy models were used by DLR in a number of studies for the development of normative scenarios (e.g., Krewitt et al. 2009; Teske et al. 2018; Simon et al. 2018; Teske et al. 2019).

The model structure is based on socio-technical scenario work done in the frame of the Helmholtz Alliance ENERGY-TRANS (see Pregger et al. 2019). We calibrated the model for the base year 2010 using statistical information from the official energy balances (AGEB 2017). The *Reference* scenario was then characterized according to a published scenario study commissioned by the German Federal Ministry for Economic Affairs and Energy (Schlesinger et al. 2014), depicting a likely German reference development in the energy sector until 2030 and its trend until 2050. Electricity demand for the sectors industry, residential, and services and commerce are set identically in the *Reference* and the *Free Play* scenarios assuming the same efficiency development. Electricity demand in the *Regulated Shift* scenario is assumed according to normative scenarios which are in line with CO_2 emission and efficiency targets of the Federal Government, namely the 'Target scenario' from Schlesinger et al. (2014) and the 'Long-term scenarios' from Pregger et al.

Table 2
Energy reduction potentials for rail vehicles from technical and operational measures in the three scenarios for 2040. Own calculation based on VDE 2013.

Scenario	Tram	Metro	Regional train	Long-distance train	Freight train
Reference	−17%	−20%	−22%	−11%	−15%
Free Play	−18%	−23%	−23%	− 8%	− 6%
Regulated Shift	−27%	−33%	−29%	−17%	−22%

Table 3
Main energy scenario parameters for 2040: energy demand structure and RES shares.

Parameter	2010	Reference 2040	Free Play 2040	Regulated Shift 2040
Final electricity use and transformation losses [TWh/yr]:				
Electricity for stationary use	510	467	467	382
Electricity for transport	20	34	17	100
Electricity for hydrogen	0	1	0	26
Electricity for energy sector and losses	83	72	74	54
RES share of power generation	16%	>50%	40%	78%
Total (and RES) power generation capacities [GW]	169 (60)	231 (157)	206 (115)	252 (200)
Heat demand end use sectors [PJ]	5 260	4 170	4 170	3 300
RES share heat generation	11.5%	33%	33%	43%
Primary energy demand [PJ]	14 480	10 500	11 100	8 560

(2013). All scenarios presume decreasing intensities of the 'classical' consumers, but increasing demand due to the implementation of heat pumps, electric boilers, and electric vehicles. These studies were also used to derive storylines and consumption trends for shipping. For air traffic, scenarios developed as part of the VEU project (Hepting et al., 2020)and own assumptions on the development of biofuel content based on EU regulation were taken into account. The scenario building resulted in detailed data sets of installed capacities in the power system, their utilization and related direct emissions from power and fuel generation.

This resulted in a successful continuation of the German 'Energiewende' regarding renewable energy expansion in power generation (around 78% renewable electricity in 2040) in the *Regulated Shift* scenario (Table 3). In contrast, this share is around 50% in the *Reference* case without additional politically set incentives and assumed to be only 40% in the *Free Play* scenario, corresponding to a halt to the further expansion of renewables after 2020 (achieved RE share of gross electricity generation in Germany was around 38% in 2018 (BMWi 2019)).

For the estimation of future annual emissions we enhanced the energy scenario model with direct emission factors for thermal power generators and other stationary processes. We derived emission factors from emission estimates and factors provided by the German Environment Agency (UBA 2015), used for emission reporting. Due to different data structures for scenario modelling and emission calculation, the assignment of emission factors could only be made on an aggregated level. However, we applied a top-down calibration using a bottom-up calculation for the energy sector from emission reporting (UBA 2016a). We calibrated our emission estimation for the years 2009, 2011, 2012 and 2014 and assumed constant emission factors for each fuel and technology until 2040. We choose this "worst case" option as a conservative approach as changes in air pollution regulation are unknown for the long-term future. Thus, future changes in the average emissions from electricity supply are mainly a result of changes in the generation mix. In addition, we estimated emissions for the supply of fossil fuels in terms of emissions from industrial processes. We derived direct emission factors referring to MJ consumed oil products from the demand of the whole energy system, the corresponding fuel consumption in transportation and estimated emissions in the conversion sector according to the official German emission reporting (UBA, 2016). Detailed information on the resulting emission factors can be found in (Seum et al. 2020).

In an increasingly electrified transport system, impacts shift from direct emissions to emissions in the power sector. Depending on total electricity demand and deployment pathways for renewable energies the generation mix results in different average emissions of CO_2 and air pollutants. The results depend strongly on the overall share of renewable energies. They are not affected by the detailed technology structure, e.g. solar-wind ratio, as upstream emissions for the production of the generation plants and additional infrastructures in the power grid are not taken into account.

We assumed the average electricity generation mix also for the supply of the EV fleet and hydrogen production systems. This represents a compromise between the possible worst case, where additional and primarily inflexible demand from transportation is covered in all hours without excess power from RES by fossil backup power plants, and the possible best case, where a highly flexible EV charging and hydrogen generation is supplied by 100% renewable electricity. The simplification replaces detailed, assumption-driven modeling of load balancing in spatial and temporal resolution. The approach is also justified by the results obtained so far from such energy system models investigating the system effects of controlled charging under different boundary conditions (see e.g. Luca de Tena and Pregger 2018).

3. Results

In the next sections we first present the fleet developments in the three scenarios for the various transport modes and their related direct emissions. We further identify the related energy consumption and impacts from the energy system. Finally we close with an overview over combined CO_2 and air pollutants emissions.

3.1. Technology development and energy demand of vehicle fleets

3.1.1. Passenger cars

The resulting development of the passenger car stock following these three pathways is shown in chapter 2.1. In the *Reference* scenario, conventional diesel and gasoline powertrains see a decrease in sales and are continuously substituted by full hybrid powertrains (G-HEV, D-HEV) that make up for more than 55% of the passenger car stock of 43 million cars in 2040 (Fig. 3). PHEVs as highly electrified vehicles are 7.5 million in number (20% of the stock). Due to comparatively high H_2 prices and relatively low H_2 infrastructure coverage, FCEVs are not seen in the market. Natural gas vehicles (CNG) sum up to around 1%. Full hybrid powertrains are also dominating the stock of 45 million cars in the *Free Play* scenario in 2040. PHEVs and CNG vehicles, however, have very little shares (below 2%), while battery electric and fuel cell vehicles are not in the market at all. The *Regulated Shift* scenario shows a very different picture in 2040. Here of the total stock of 35 million cars, BEVs reach 5.5 million cars and PHEV 9.9 million (15% and 30% of the stock resp.). Other full hybrid powertrains represent around 55% of the stock. As prices for conventional fuels are comparatively high and H_2 infrastructure coverage is relatively mature, FCEV are able to gain relevant market shares (2% of the stock) and thus conventional powertrains are only with 14% in the market, with 1.1 million are diesel and 3.7 million are gasoline vehicles. As in the *Reference* scenario, the cost- and CO_2-wise competition between CNG vehicles, PHEV and HEV leads to low shares of CNG in the *Regulated Shift* scenario (<1% in stock in 2040).

The development of the overall energy consumption is determined by the total amount of vehicles in stock, the energy efficiency of the vehicles and the market composition of the vehicle fleet. The resulting energy consumption of the *Reference* scenario shows the potential of increased drive-train efficiency, as despite an increasing number of vehicles in stock, the overall energy consumption decreases (Fig. 4). Main driver for this development is the hybridization of the conventional drive-train. In the large vehicle segment, a major hybridization trend as well as a shift from diesel to gasoline vehicles takes place leading to a slight increase in total gasoline consumption from 2030 to 2040. The same mechanism applies for the *Free Play* scenario. In both scenarios, the overall energy consumption decreases by about 40% in 2040 compared to 2010 (Fig. 4). In the *Regulated Shift* scenario, the absolute amount of vehicles in stock decreases and the vehicles in stock show a high share of electrified and energy efficient drive-trains. Therefore, the energy consumption decreases by 57% from 2010 to 2040. The share of electricity in this case is 20%. It is smaller than the share of BEVs and PHEVs in stock, as the electric drive-train is more energy efficient than combustion drive-trains. The use of hydrogen is still low due to the small amount of FCEVs in the vehicle stock. The results show that in all scenarios, the use of gasoline and diesel fuels still are the main contributors the overall energy consumption of passenger cars. Comparing the results with data for the German passenger car market of 2019, the current path follows the reference scenario in terms of market shares and absolute numbers compared to current vehicle stock data taken from (KBA, 2020). The vehicle market in 2020 is dominated by conventional ICE vehicles in all scenarios. In case of the reference scenario, the projected number of vehicles meets the number reported in January 2020 (KBA 2020) with an accuracy of 3% in case of diesel and 13% in case of gasoline vehicles. The numbers for electrified and CNG vehicles are actually lower in reality than in our 2020 results, e.g. around 100,000 PHEVs reported in January 2020 compared to 300,000 in our model. Due to the low number of these vehicles, the model loses accuracy and uncertainty of absolute number increases. In terms of shares of alternative drive-trains in the vehicles stock, we overestimate the number of HEVs, PHEVs and BEVs to a certain extent. In the actual stock hybrids cover 1% compared to 3% in our model; BEV share is 0.3% in reality and 0.4% in our calculation. For the other scenarios, the findings of a comparison with current stock data are very similar for the year 2020, though the overall number of vehicles is underestimated in both cases (10% in the free play and 15% in the regulated shift) (see Fig. 5).

3.1.2. *Light and heavy duty vehicles for freight transport*

For each of the seven relevant power train technologies considered of the seven reference vehicles, the market share is estimated for the years 2010, 2030 and 2040 in the single scenarios. Up to 2020, light and heavy duty vehicles are dominated by diesel cars, representing almost 90% of the vehicle stock (statista, 2020). Diesel vehicles are almost as dominant as in 2010.

The *Reference* scenario is based on the assumption that although there is no hard obligation to make major changes, there are still CO_2 target values for the vehicles. At the time of our modelling, only light duty vehicles were affected by the European fleet targets. Nonetheless, we assumed that HDV vehicles would be included in the CO_2 reduction policy after 2020. A moderate reduction in the emission target values can be responded to with a high proportion of MHEV. We further assume entry restrictions in city centers. This promotes the market entry of battery electric vehicles.

In the *Free Play* scenario, the structure of the vehicle stock remains diesel-dominated. The expected "battery jump" does not take place, so that electric mobility remains a niche application. Instead, natural gas will play an important role as an alternative form of propulsion during the transition period. In this respect, a natural gas scenario could also be talked of for commercial transport. For the

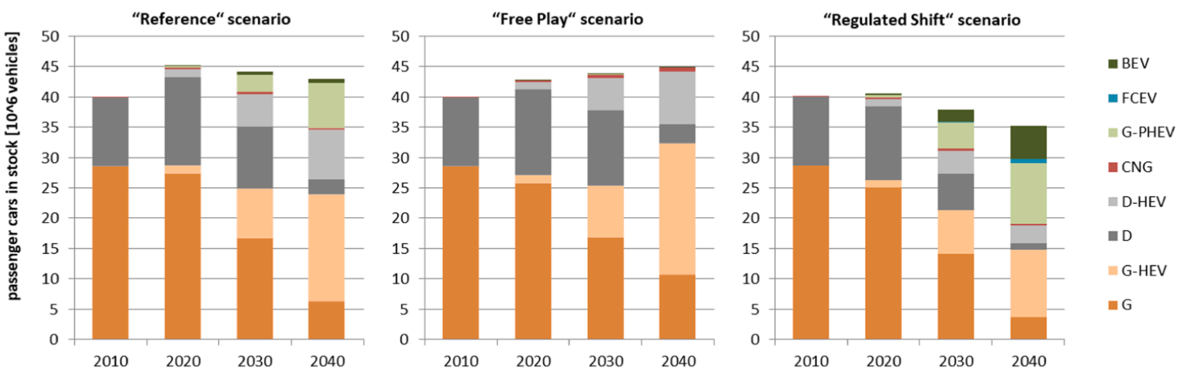

Fig. 3. Composition of the passenger car stock in Germany for the three scenarios.

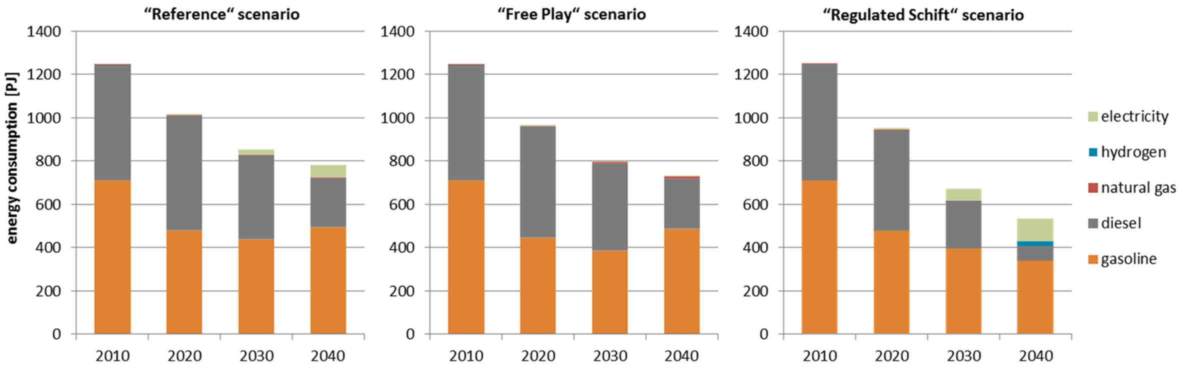

Fig. 4. Total energy demand of passenger cars in Germany by fuel for the three scenarios based on WLTP energy consumption and average mileage per vehicle.

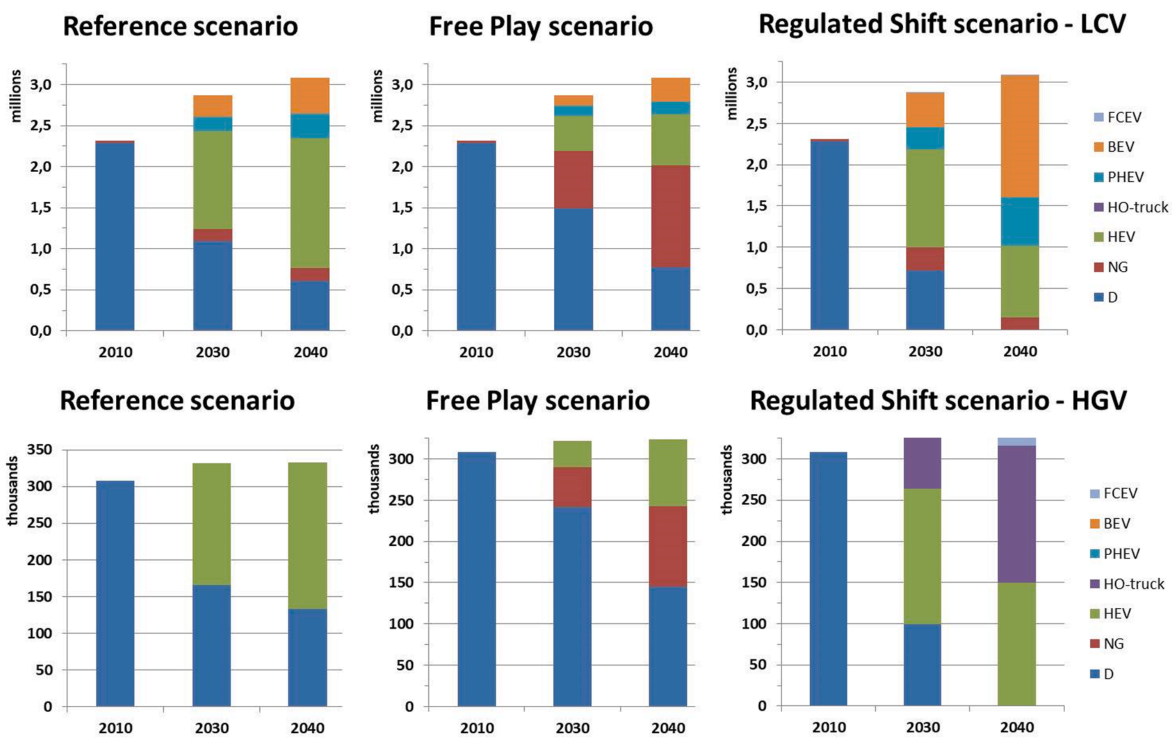

Fig. 5. Development of the LDV and HDV stocks in the three scenarios.

end customer, hybrids mean that they make a small contribution to protecting the environment.

The *Regulated Shift* scenario is a purely electrical scenario. It includes the tightening of CO_2 target values for both LDV and HDV. This tightening requires electrification; support mechanisms for electric drives are driving it forward. The overhead line system for heavy trucks will be implemented EU-wide beyond an isolated solution in Germany. The infrastructure for this system (trolley system etc.) will be financed via the market, e.g. via a toll levy. For other electrical power units, there is a sufficient and functional fast-charging infrastructure. Gas vehicles remain in a niche - the costs of the necessary refuelling infrastructure cannot be borne by the market, but only by the individual users of gas vehicles themselves. Therefore, this technology is not a competitive option. Likewise, FCEV power units can only be used in niches.

3.1.3. Rail-based transport and buses

The energy demand per passenger kilometer travelled is derived from the base-year energy consumption per seat-km, combined with energy efficiency improvements (Table 3) and changes in the vehicle utilization (Table A2). As a result the energy consumption per passenger kilometer is calculated. The largest improvement appears in the *Regulated Shift* scenario, due to both, technological measures and increased utilization. However, even in the *Free Play* scenario with a reduced utilization rate of public transport, the overall energy demand per passenger kilometer declines, except for public buses (Table 6).

For rail-based freight transport a similar approach was chosen. The two influential factors are energy efficiency improvements due to technical and operational measures (Table 3) and the share of diesel propulsion for the freight trains. To simplify, we calculated an average energy consumption rate of 0.116 MJ per ton-kilometer for electric drive and 0.313 MJ/tkm for diesel propulsion. The technological and operational improvements lead to the energy used per ton-kilometer according to Table 4.

In case of the total energy demand from rail-based public transport, the scenario transport demand in differentiated in near distance bus, rail public transport and long distance rail transport. The total energy demand from public transport and rail freight is presented in Table 5. Analogous to the passenger demand, rail freight transport demand was modelled using the DEMO transport demand model. Here a significant modal shift is only visible in the Regulated Shift scenario from road to rail freight transport (Winkler and Mocanu 2020).

3.2. *Regulated emissions from vehicles*

3.2.1. *Passenger cars*

Due to technology improvements, the CO_2, CO, NO_x emissions of a conventional vehicle decrease in all scenarios. (For the derivation of the scenario emission factors see Seum et al. 2020) A further reduction is achieved through an increasing share of electric driving per vehicle in particular in the *Regulated Shift* scenario. CO_2 emissions directly correspond to the use of gasoline and diesel in the vehicle stock (Fig. 6). NO_x emissions remain high for vehicles using a diesel engine, both in the case of conventional and hybrid electric vehicles. Thus the NO_x emission factors for an average passenger car in the *Reference* and *Free Play* scenario remain more than twice as high as in the *Regulated Shift* scenario. Overall substantial air pollutant emission reduction per vehicle can be expected in all scenarios and regardless the technological pathway (Fig. 6).

Consequently, the overall emission of the passenger car fleet decrease in all scenarios from 2010 to 2040 for the considered emissions to air. The CO_2 emissions are reduced by 21% in the *Free Play* scenario and by 66% in the *Regulated Shift*. Considering the fleet reduction target of 37% until 2030, which was not in place yet when the presented calculations have been executed, only the *Regulated Shift* scenario with a 40% reduction until 2030 would meet these requirements. As the model approach for the vehicle shares is cost driven, the average CO_2 emissions reflect the cost trends of the single technologies in the different scenarios (including fuel prices) as well as the fleet targets and the actual emission factors as described in chapter 2.3. Especially the comparatively low prices for conventional fuels lead to a higher usage of these fuels in the *Reference* and *Free Play* scenarios and thus higher average CO_2 emissions.

NO_x and PM emission are also substantially reduced in all scenarios (Table 6). Main drivers for this trend are lower on-road emissions of future combustion engine drive-trains and above all the technology shift from diesel towards gasoline engines and a higher grade of electrification. Though CO emission decrease, the reduction potential is less distinctive as CO emissions are predominantly emitted by gasoline internal combustion engines which still play a major role in the future passenger car market.

3.2.2. *Light and heavy duty vehicles for freight transport*

Similarly to passenger cars is the decline of NOx and PM from LDV and HDV vehicles regardless the technology path, although the electrification in the *Regulated Shift* scenario further reduces those emissions. With regard to CO, the high share of natural gas in the Free Play scenario lead to an increase in CO emissions. However, the data on emissions from natural gas vehicles is sparse and carries a degree of uncertainty. With regard to CO_2 emissions, the natural gas pathway in the *Free Play* and the electrification pathway in the *Regulated Shift* scenario significantly contribute to the reductions.

Specifically the application of HDV with overhead electricity on highways has great potential to reduce the greenhouse gas impact of road freight transport, as it can be seen in the results of the *Regulated Shift* scenario. Table 7 lists the emission development for LDV and HDV vehicles. In all scenarios, the average CO_2 emissions per tkm are reduced until 2030 compared to 2018. The *Reference* and *Free Play* scenario both show reductions of about 20%. The *Regulated Shift* scenario indicates a reduction by about 30% which would meet the current regulation on emission savings for HDV, but not for LDV (31% reduction until 2030 required). Yet as travel demand increases at the same time, total absolute CO_2 emissions cannot be reduced equally. A further reduction on a vehicle level is not feasible within the presented scenarios, as in the *Reference* scenario the price trends reflect the state of knowledge in 2018. In the *Free Play* scenario only HEV and CNG vehicles are have competitive TCO compared to conventional vehicles. As the commercial vehicle sector is

Table 4
Development of the energy consumption of public transport and rail freight for base-year and the three scenarios for the year 2040 [MJ/pkm].

Scenario	Public bus, diesel [MJ/pkm]	Tram & Metro, electric [MJ/pkm]	Regional train, electric [MJ/pkm]	Regional train, diesel [MJ/pkm]	Long-dist. train, electric [MJ/pkm]	Rail freight, electric [MJ/tkm]	Rail freight, diesel [MJ/tkm]
Base-year 2010	1.02	0.45	0.48	1.21	0.25	0.12	0.31
Reference	0.88	0.32	0.35	0.88	0.19	0.01	0.29
Free Play	1.09	0.40	0.43	1.08	0.25	0.11	0.30
Regulated Shift	0.81	0.19	0.26	0.66	0.15	0.09	0.28

Table 5
Total energy demand of public passenger transport and rail freight for the base-year and the three scenarios in 2040 [PJ].

Scenario	Public bus, diesel	Public bus, fuel-cell	Passenger rail regional & long-dist., electric	Passenger rail regional & long-dist., diesel	Passenger rail, fuel-cell	Rail freight, electric	Rail freight, diesel
Base-year 2010	49.8	–	37.5	10.1	–	12.0	1.2
Reference	46.6	1.5	29.0	4.8	0.8	14.2	0.9
Free Play	51.3	–	31.1	6,0	–	14.6	0.9
Regulated Shift	46.0	11.8	30.3	2.2	1.9	20.0	1.2

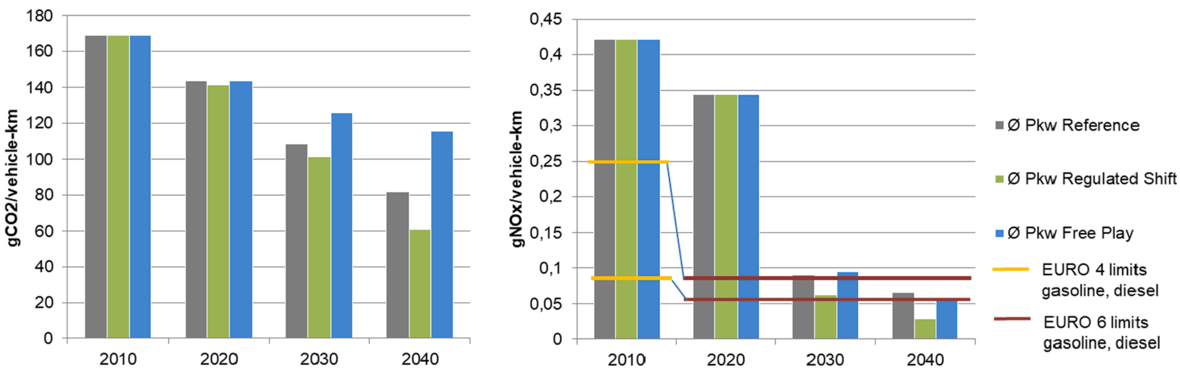

Fig. 6. Development of fleet-wide passenger car emissions of CO_2 and NO_x for the three scenarios.

Table 6
Direct emissions from passenger cars in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	107 478	728	270	7.95
Reference	59 435	402	48.3	1.20
Free Play	84 475	489	43.1	1.49
Regulated Shift	36 518	308	18.2	0.73

Table 7
Direct emissions from LDV and HDV in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	45 342	81	258	8.40
Reference	55 896	46	61.3	0.92
Free Play	50 920	166	60.8	0.69
Regulated Shift	25 816	31	40.4	0.63

very cost sensitive, a further reduction of the vehicle CO_2 emissions is unlikely under the given conditions.

3.2.3. Rail-based transport and buses

A majority of the emissions from public transport and rail-based freight transport is associated with the electricity generation, because of the dominant electric propulsion technology. However, the public buses and a residual share of diesel propulsion of rail cars generate direct emissions. Tables 8-11 list the direct emissions from regional trains, public buses, coaches and freight trains. The

Table 8
Direct emissions from diesel fueled regional trains in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	750	0.9	9.5	0.14
Reference	356	0.4	4.5	0.07
Free Play	443	0.6	5.6	0.08
Regulated Shift	160	0.2	2.0	0.03

emissions from diesel freight trains increase in the *Regulated Shift* scenario due to a substantial increase in overall rail freight.

3.3. Emissions from energy supply

Fig. 7 shows the resulting overall electricity generation structure for each scenario and scenario year. The resulting emissions from energy supply are shown in Table 12 for electricity and refinery fuels. As expected, the differences are high due to the assumed changes in the power generation mix in the long-term future, with by far the lowest values in the *Regulated Shift* scenario for all considered pollutants and CO_2. The additional emissions from fossil fuel production are estimated to be much lower compared to electricity generation.

The emission calculation shows that both the *Free Play* and the *Regulated Shift* scenario reduce the emission factors for fuels around 20–25% compared to the *Reference* case. Direct CO_2 emissions per fuel unit increase in the Regulated Shift scenario compared with Reference.

However, these effects are rather small compared to the change in emissions in the power sector. In the Free Play scenario market forces lead to an even higher share of coal in the power sector. Most average emission factors for electricity generation increase here up to 20–30%. Still, the impact of the higher emissions in the Free Play scenario is low, compared to the Reference scenario, due to low electrification. On the opposite the power emission factors in the Regulated Shift scenario decrease between 30 and 60% compared to Reference. Here, the high share of renewable energy in the Regulated Shift scenario leads to the lowest emission factors in all scenarios, which is essential for an overall emission reduction of the transport system.

3.4. Overall emissions from the combined transport and energy scenarios

The presented information on overall energy demand and emissions from the different transport modes is the base for calculating the overall transport induced emissions for the three scenarios. This allows analyzing the contribution of each transport mode, detecting potential emissions shift from transport to the energy sector and quantifying the overall differences between the scenarios.

A comprehensive reduction of emissions and greenhouse gases from transport comes along with a shift towards electrification. This electrification in the transport sector takes place as new hybrid, battery or fuel-cell electric propulsion technologies in vehicles or by shifting transport demand to electrified transport and rail. Our modelling of transport demand indicates that the assumed measures to promote modal shift will not be sufficient for the set CO_2 reduction targets (e.g. the German target to reach < 98 mill. tons transport CO_2 in 2030, Fig. 8). Particularly in the *Reference* and *Free Play* passenger vehicle miles travelled remain high. Nonetheless the emission reductions particularly from the introduction of plug-in hybrid and battery-electric technologies in passenger cars and light duty vehicles are significant. The shift of passenger cars and light duty vehicles to hybrid technologies, together with efficiency improvements, lead to a 45% reduction of CO_2 emissions in the *Reference* scenario. In contrast, in the *Free Play* scenario, where passenger cars are larger, shares of hybrid electric vehicles lower and battery electric vehicles negligible, the CO_2 reduction in passenger transport is only 26% in 2040 compared to 2010. Large expectations for reducing emissions have been expressed in the context of electrifying vehicles. In our *Regulated Shift* scenario the transport system moves in this direction, although pure battery electric vehicles and fuel-cell vehicles only enter the market in significant numbers from 2025 onwards. Passenger transport's CO_2 emissions are reduced by approximately 65% (Fig. 8).

Compared to CO_2 emissions, the emissions of NO_x and PM decrease considerably (Fig. 9). NO_x emissions decrease by almost 80% for the *Reference* and *Free Play* scenarios and by 85% in case of the *Regulated Shift*. PM reductions are in a similar range. In both cases, the decreasing share of internal combustion engines and especially diesel vehicles in the passenger car and commercial vehicle fleet is the main reason for these emission reductions. Higher electrification in the *Regulated Shift* adds to this trend. CO emissions though show lower reduction potential, especially in the *Free Play* scenario due its specific technology mix in the commercial vehicle market. But also for passenger cars, the CO emissions decrease to a lower extend compared to NO_x and PM due to the high share of gasoline fueled vehicles. As the energy system shift towards renewable electricity, the emissions are barely shifted from the transport to the energy sector in 2040. In all scenarios, the main drivers for emission reductions are the changes in passenger and commercial road vehicle markets. As other transports modes show higher efficiency per km and even gain efficiency until 2040, their contribution to the transport emissions remain small despite of the modal shift that takes place in our scenarios.

4. Discussion

In our quantitative analysis we show the impact of different political and economic scenario settings on the development of technologies and emissions from land transport. The explorative scenario analysis created the development paths in a systems

Table 9
Direct emissions from public buses in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	3 161	3.9	23.4	0.32
Reference	2 418	0.5	1.3	0.12
Free Play	2 694	0.5	1.4	0.14
Regulated Shift	2 322	0.5	1.2	0.12

Table 10
Direct emissions from coach buses in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	521	0.9	4.6	0.10
Reference	1 030	0.4	1.2	0.02
Free Play	1 099	0.4	1.3	0.02
Regulated Shift	1 083	0.4	1.3	0.02

Table 11
Direct emissions from diesel rail freight in 2010 and in 2040 in the three scenarios [in 1000 t].

Scenario	CO_2	CO	NO_x	PM_{10}
Base-year 2010	90	0.3	1.6	0.04
Reference	63	0.2	1.2	0.03
Free Play	68	0.2	1.2	0.03
Regulated Shift	85	0.3	1.7	0.05

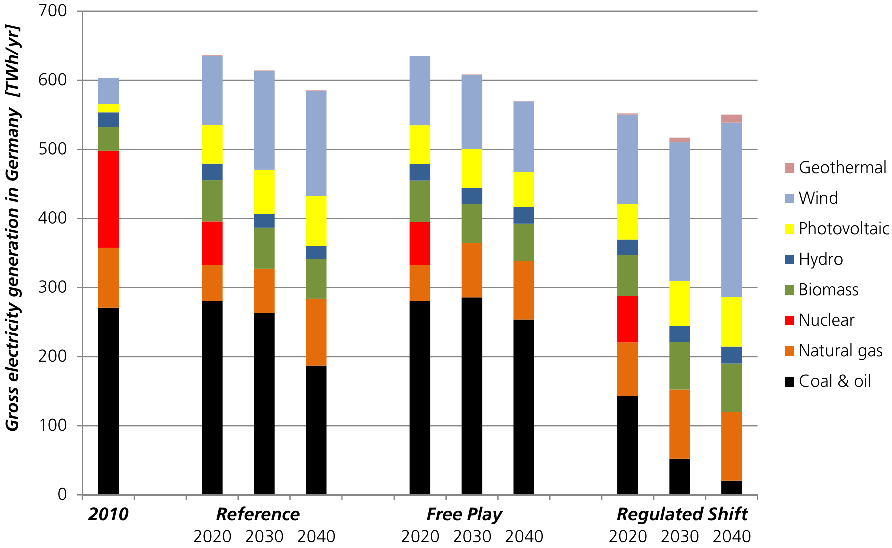

Fig. 7. Power generation structure in the three scenarios.

Table 12
Emissions from power generation and refineries for fuel production in 2010 and scenario year 2040 (total and in brackets for transport only).

Scenario	Production (demand)	CO_2	CO	NO_x	PM_{10}
Power generation	**TWh**	**million t**	**1000 t**	**1000 t**	**1000 t**
Base-year 2010	630 (20)	314 (10.3)	118 (3.9)	266 (8.7)	8.2 (0.3)
Reference	593 (34)	186 (11.2)	81 (4.9)	165 (10.0)	5.7 (0.3)
Free Play	578 (17)	237 (7.4)	91 (2.8)	192 (6.0)	6.6 (0.2)
Regulated Shift	556 (1 0 0)	48.5 (10.6)	53 (11.6)	87.8 (19.2)	2.5 (0.5)
Refineries	**PJ***	**million t**	**1000 t**	**1000 t**	**1000 t**
Base-year 2010	4 300 (2 460)	20 (11.4)	1.7 (0.95)	17.8 (10.2)	2.9 (1.7)
Reference	3 300 (2 350)	12.3 (8.8)	1.2 (0.86)	12.0 (8.6)	1.7 (1.2)
Free Play	3 460 (2 490)	12.5 (9.0)	1.2 (0.87)	12.0 (8.7)	1.7 (1.2)
Regulated Shift	1 800 (1 300)	7.0 (5.0)	0.5 (0.38)	5.3 (3.8)	0.7 (0.5)

* Total refinery output of oil products including for non-energy use.

approach, focusing on plausible and consistent interdependencies. Beyond a single vehicles level, we analyze the energy consumption and emissions on a fleet level in order to provide a sound picture of the consequences of different measures that affect the land transport market. In terms of energy efficiency and overall emissions, the *Reference* and *Free Play* scenario do not differ much, despite significant differences in the story line. In both scenarios, transport demand increases both for road-based passenger and for freight transport. The CO_2 emissions from transport in those scenarios remain high and reduction targets (set for 2030) will not be met, even in

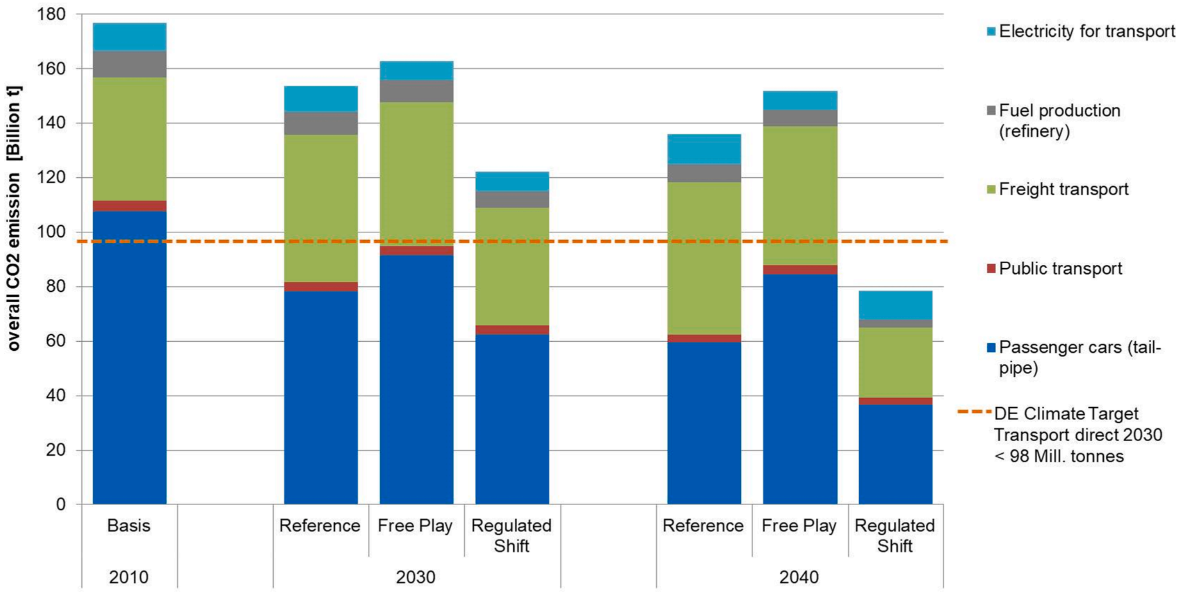

Fig. 8. Comparison of overall CO_2 emissions of land transport in the three scenarios.

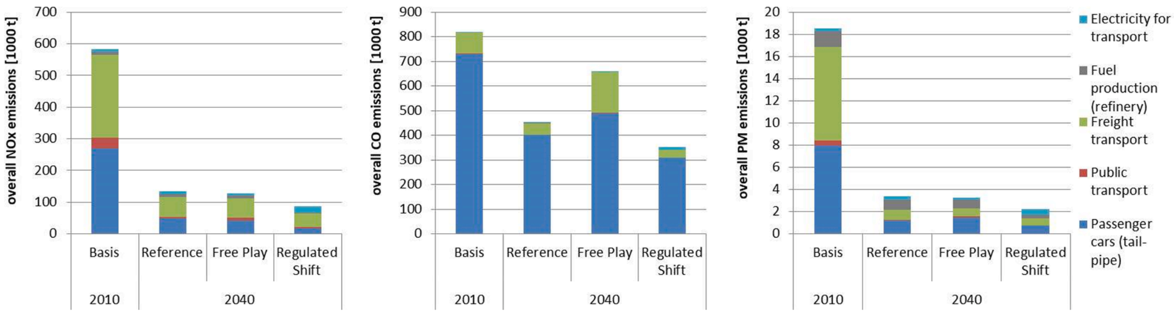

Fig. 9. Overall pollutant emissions of land transport in the three scenarios.

the year 2040. In the *Reference* scenario, some progress with regard to CO_2 reduction is expected through efficiency improvements, complemented by moderate electrification. However, uptake of electric vehicles falls short of expectation if incentives are not ramped up and combined with dis-incentivizing conventionally propelled vehicles. Furthermore, reductions of passenger transport are offset by increases in freight transport. The *Free Play* scenario performs even worse, because of the trend to larger and higher powered vehicles combined with a lack of alternatives to the private car. While the *Free Play* scenario does not reflect current policy goals, its developments are a continuation of currently visible trends: low fossil fuel prices, more, larger and higher powered cars, a lagging shift to alternative propulsion, and a thwarted shift to renewable electricity. Our analysis of the *Free Play* scenario therefore exemplifies a development path where society does not steer more strongly against observable trends. Only the *Regulated Shift* scenario reveals significant potentials or energy and CO_2 savings, due to a combination of behavior change and strong technological progress. Only here the transport demand by passenger cars declines and a sizable modal shift takes place. This is significant, since in the *Reference* scenario 2040, efficiency of public transport remains nearly twice and in the *Regulated Shift* even more than three times better per passenger-kilometer than passenger car transport. As Winkler and Mocanu (2020) show, without a series of measures, including e.g. urban sustainability policies, restrictive parking management, and the promotion of alternatives to the private car, a shift from private car to public transport is not likely to happen. While all scenario pathways follow the maxim of being plausible and thinkable, the *Regulated Shift* would require substantial efforts, technological progress and infrastructure investments. The passenger rail would, for example, need to carry 50% more passengers in 2040 and freight rail transport nearly twice the amount of ton-kilometer compared to 2010. Furthermore, even in the *Regulated Shift* scenario, the 2030 CO_2 targets would not be met, if large parts of the freight transport were not electrified.

Besides modal shift, technical improvements are the main drivers for the overall emissions reductions. Such improvements become more dynamic with stronger societal support of alternative technologies. In case of pollutant emissions of road vehicles, a combination of more stringent regulations for in-use conformity and the financial incentive of advanced propulsion technologies lead to a decrease of on-road emissions. Overall, within the settings of the consistent and explorative scenario approach, the taken measures are not sufficient to meet the 2030 national CO_2 reduction target. Additional factors like the use of synthetic fuels and the ban of combustion engine vehicles are possible, but would require further regulatory and technological activities that have not been in line with the overall rather moderate scenario storylines at the time when we developed them. Without an electrification of long-distance freight transport, most achievements in emission reductions of passenger transport in the *Regulated Shift* scenario are thwarted by strong increases in freight transport emissions. In the *Regulated Shift* we have calculated the electrification of long-distance freight transport by means of introducing hybrid-electric trucks that utilize overhead electric lines on all major motorways. Only in this case the freight transport CO_2 emissions are reduced by 17% in 2040 compared to 2010. Nevertheless, the electrification of long-distance freight transport might be better implemented with long-distance freight transport on rail, particularly considering other pollutants such as particulate matter. Both would require large investments and would be administratively difficult to implement. Thus, one might contest the probability of the electrification of freight transport, even in the context of the *Regulated Shift* scenario. While the criteria of plausibility and consistency are of great importance in the VEU scenario storylines, they too depend on subjective assumption in several places.

The CO_2 benefits from electrification of transport depend on the share of renewable energies and of coal as energy source and are very limited in the *Reference* and *Free Play* scenario. The results of the modelling on the energy side depend on scenario-specific assumptions on the power generation split. In the case of the *Regulated Shift* scenario, a detailed and prospective consideration of the future use of biomass in the energy sector could provide a more substantiated result for the remaining emissions. The use of emission factors in the energy model proved to be difficult to implement, as very different data structures exist in emission reporting and scenario modelling. Even if a top-down calibration with the official national emission calculations could be carried out, methodological weaknesses arise in the projection of the emission calculations. A calibrated bottom-up modelling would reduce the uncertainties in future estimations.

5. Conclusion

The determination of future energy consumption and emissions in the transport sector is based on a detailed bottom-up approach. It becomes clear that the development of technologies, fleets and their use are decisive factors in reducing the use of fossil energies, besides the modal shift to rail. Successful emission and CO_2 abatement strategies require to implement a systems approach and to design a multitude of measures and investments that include both, carrots and sticks. The scenario results show that the for air pollutants the future scenario pathways are less variable due to strict regulations (e.g. around 80% reduction in case of NO_x emissions). In case CO_2 emissions, results vary from 26% to 65% reduction potential. Following the development path of the *Regulated Shift* requires the implementation of ambitious measures, incentives, regulations and investment in infrastructure as fast as possible. Neither a *Reference* pathway without ambitious policy measures nor market driven technology developments of the *Free Play* will achieve climate targets. The time lag of fleet development leaves still some time to put additional pressure on the power sector, to reduce its CO_2 emissions and to phase out coal. However, the explorative approach of our scenarios ends up with significant remaining emissions even in the most far reaching *Regulated Shift* scenario. Further efforts and more dynamic transition processes are required for a mitigation pathway which is in line with the targets of the Paris Agreement.

This paper also underlines the importance of assessing future developments in the transport sector towards electrification and also electricity-based synthetic fuels, taking into account future changes in energy supply. This was quantitatively investigated by means of a combined scenario analysis with the aim of determining total emissions of CO_2, the most important greenhouse gas, and selected air pollutants. The combined scenario analysis demonstrates that only a joint de-carbonization of both transport and electricity systems can lead to a significant reduction of emissions. A fast phase out of fossil fuels in Germany, above all lignite and hard coal, and in parallel a further substantial growth of renewable power generation are mandatory to stay within the remaining greenhouse emission budget and to achieve a significant share of renewable energy in the transport sector.

CRediT authorship contribution statement

Simone Ehrenberger: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Formal analysis. **Stefan Seum:** Conceptualization, Writing - original draft, Writing - review & editing, Formal analysis, Project administration. **Thomas Pregger:** Writing - original draft, Writing - review & editing, Methodology, Formal analysis. **Sonja Simon:** Writing - review & editing, Methodology, Visualization, Formal analysis. **Gunnar Knitschky:** Writing - original draft, Writing - review & editing, Formal analysis. **Ulrike Kugler:** Methodology, Formal analysis.

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.

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Appendix A. Supplementary data

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