35th International Electric Vehicle Symposium and Exhibition (EVS35)
Oslo, Norway, June 11-15, 2022

Development of a scenario model for the simulation of the technology diffusion in the commercial vehicle market in Germany

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Summary

The absolute CO_2 emissions of German road freight transport increased by 21 percent since 1995. However, the national target is to decarbonize the traffic-related CO_2 emissions by 2045. This paper presents a scenario model to simulate the diffusion of alternative powertrains and energy carriers in the road freight vehicle market as well as the resulting energy demand in Germany until 2050. A scenario analysis compares three technological set-ups to climate neutrality. The results show a rapid market diffusion of battery-electric vehicles in all scenarios. However, the strengthening of CO_2-Regulation is necessary to achieve the climate targets with increasing transport demand.

Keywords: alternative fuel; energy consumption; freight transport; market development; Powertrain

1 Introduction

The specific CO_2 emissions of German road freight traffic per transport performance (in ton-kilometers) have decreased by 32.6 percent between 1995 and 2020, due to technological progress in engines and fuels. Nevertheless, the absolute CO2 emissions have risen by 17 percent in the same period, with 45,9 million tons of CO_2 emissions in 2020. This is mainly due to the rapid growth in truck traffic. Since 1991, truck traffic has increased by 103%, resulting in 486 billion ton-kilometers in 2020. [1] This led also to an increase in total vehicles in stock. From 2,22 million in 1995 to 3,28 million in 2020 mainly diesel-fueled trucks [2]. To meet the goals of the Paris Climate Agreement, CO_2 emissions in road freight transport must be reduced drastically. The European Commission defines the Green Deal as its political strategy and aims to achieve greenhouse gas neutrality in Europe by 2050 [3]. Within the Green Deal, the EU Commission specified concrete measures for the transport sector in the "Fit for 55" package, such as stricter CO_2 emission standards for cars and trucks by 2030 [4]. The German government amended its federal climate protection act in 2021 and aims to achieve greenhouse gas (GHG) neutrality already by 2045 (the previous act defined 2050). Specifically for heavy-duty vehicle traffic, it is also defined that around one-third of the transport performance should be driven electric or based on electricity-based fuels by 2030. [5] In addition, the German government has defined energy efficiency targets in its "Energy Efficiency Strategy 2050". The goal is to reduce the final energy consumption in the transport sector by around 40% by 2050 compared with 2005 levels. In conclusion, the challenge today is to achieve stricter targets for energy efficiency and CO_2 emissions in transport as demand for transport continues to rise. According to the German Ministry of Transport forecast, road freight transport performance is expected to increase to 607.4 billion tkm in 2030. A 25 % increase compared to 2020. [6]

From today's perspective, a combination of different measures in road freight transport is necessary to achieve the required reduction targets. A particular focus is on vehicle efficiency technologies such as battery-electric powertrains. This raises the question of which technological paths in road freight transport are suitable for achieving the national GHG target, considering the framework conditions in the freight vehicle market. This paper presents a scenario model to simulate the technology diffusion of alternative powertrains and energy carriers in the road freight vehicle market as well as the resulting energy demand in Germany until 2050. A scenario analysis compares three different technological set-ups: Electric mobility, Hydrogen and Synthetic fuels, to climate neutrality. The results show a rapid market penetration of battery-electric freight vehicles in all scenarios. However, the strengthening of CO_2 regulation in the transport and energy sectors is necessary to achieve the climate targets with increasing transport demand until 2045.

The analysis was carried out within the framework of the project “BEniVer: BEgleitforschung Energiewende im Verkehr - accompanying research on the energy transition in transport”, which is funded by the German Federal Ministry for Digital and Transport [7]. The project aims to investigate the development of renewable fuels and network with other research projects of the initiative “Energiewende im Verkehr” to leverage synergy potentials.

In the following, the methodical structure of the scenario model is presented, which is divided into two sub-modules: new registration vehicle market and stock vehicle market. The third chapter summarizes the key assumptions and data for the scenario analysis. The results of the scenario analysis are then presented. This includes the market potential of alternative powertrains in the new vehicle fleet and the energy demand of vehicle stock. In chapter five, the results are discussed and a conclusion is given.

2 Methodology of the market model

The scenario market model presented follows a bottom-up approach to describe the market potential of alternative powertrain and energy carrier systems and their impact on road freight transport. The diffusion of individual technologies and energy carriers are modelled via the market adoption of the respective vehicle configuration and the mileage share of the vehicle owner in the total transport mileage. The modelling aims to show in particular the influence of efficient powertrain options and climate-neutral energy carriers on the mileage-related CO_2 emissions of the German road freight transport. The scenario market model is disaggregated into two main modules.

- New vehicle market: Market potential analysis of alternative powertrains and fuels in the new light and heavy-duty vehicle sales market (basic principle based on [8]),
- Stock market: Modelling of the yearly vehicle stocks and their yearly mileage to calculate the traffic-related CO_2 emissions

Specific market characteristics and interdependencies are considered in the individual submodules. Several input variables for the simulations that are outside the model boundaries are defined as external influencing factors (scenario assumptions). Figure 1 visualizes the structural design of the overall vehicle market scenario model.

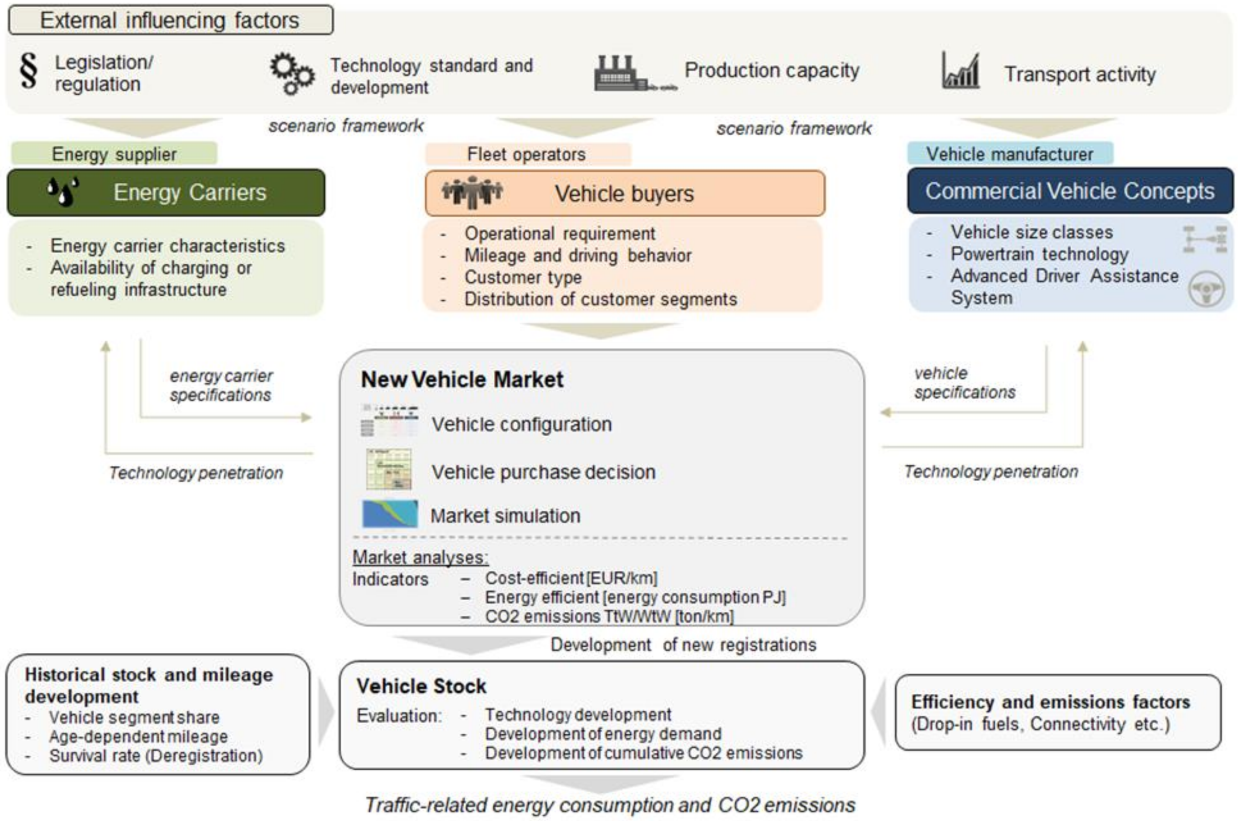

Figure 1: Schematic structure of the vehicle market scenario model

In the following sections, the individual modules of the scenario market model are presented in detail.

3.1 New vehicle market

On the supply side, the commercial vehicle concepts of the vehicle manufacturers, as well as the energy carriers of the energy suppliers, are considered. In the German road freight market, six vehicle segments can be distinguished. These can be classified according to their gross vehicle weight (GVW) into the following vehicle segments: 3.5 ton Transporter (up to 3.5 tons GVW), 7.5 ton truck (3.51 to 7.5 tons GVW), 12-ton truck (7.51 to 12 tons GVW), 18 ton truck (12.1 to 18 tons GVW), 26 ton truck (18.1 to 26 tons GVW) and 40 ton semi-trailer tractors (26.1 to 40 tons GVW). Internal combustion engine and electric powertrain systems are configured for each vehicle segment. These are ICEV (Internal Combustion Engine Vehicles), MHEV (Mild Hybrid Electric Vehicles), FHEV (Full Hybrid Electric Vehicles), PHEV (Plug-In Hybrid Electric Vehicles), REEV (Range-Extended Electric Vehicle), FCEV (Fuel Cell Electric Vehicle) and BEV (Battery-Electric Vehicle). Furthermore, the following reference fuels are mapped: Diesel, synthetic diesel, CNG (compressed natural gas), synthetic CNG, LNG (liquid natural gas), synthetic LNG, compressed hydrogen, liquid hydrogen, and electricity. Diesel, CNG and LNG represent the fuels that are available at fueling stations today. The competitive situations of individual synthetic fuel options are not represented in the market model. Only a generic synthetic fuel option is used. In addition, the market model also represents technology for automation and connectivity measured by the different automation levels. This is not used for the purpose of the presented paper and will therefore not be further described in the following. In conclusion, the differentiated modelling of the energy carriers and the powertrain options allowed the characteristics to be specified independently of one another and thus the potential to be evaluated in a differentiated manner. In total, there are 32 powertrain-energy carrier configurations per vehicle segment size.

On the demand side are the vehicle buyers, represented as the logistics fleet operators. Based on historical registration and traffic statistics, buyer groups are generated, which are represented in the model structure as simulation agents. A suitable distinction was made according to [9]. These are characterized by vehicle segments, similar as described above, the specific annual mileage and the transport task (urban delivery, regional distribution and long-haul transport) which describes the main purpose of the vehicles. In addition, there is a subdivision according to diffusion types, which differentiates the operational requirements of the buyer groups. These are the maximum depreciation period, usable payload, daily range and infrastructure density of the energy carrier. The disaggregation results in 628 simulation agents (see also [9]).

In the cost-sensitive road freight transport, the total cost of ownership (TCO) of the vehicle is crucial for the evaluation of alternatives. Means Accordingly, a comparative Relevant Cost of Ownership (RCO) evaluation of possible alternatives is useful for mapping the purchase decision. But at the same time, high reliability or unrestricted operation needs to be enabled. For the presented calculation, this means that the payload and volume of the vehicles will not be restricted (based on numbers of the reference diesel vehicles) and the daily transport demand of the simulation agents are covered by the energy capacity of the vehicles and suitable refueling and charging strategies. Additionally, the expected infrastructure availability of the simulation agent needs to be secured. For battery-electric vehicles, the purchase of the Electric Vehicle Supply Equipment (EVSE) is assumed. Therefore, the investment and operating costs for the EVSE are also included in the vehicle cost calculation. In addition, roll-out rates for megawatt chargers and hydrogen refueling stations are assumed. The annual infrastructure density is compared with the expected infrastructure density of the simulation agents. Thus, a discrete choice selection experiment is performed for each simulation agent based on the individual characteristics to analyze the best preference. In the first step, as per exclusion principle, the availability of powertrain technologies and infrastructure, calculated (electric) range and usable payload and volume are evaluated for each vehicle powertrain-energy carrier configuration. In the second step, the minimum relevant cost of ownership is calculated.

For a comparative evaluation of the vehicle concepts, the relevant cost of ownership $RCO_{i,j,k}$ are calculated, similar to the approach in [10]. These can be differentiated according to the vehicle segment i, the powertrain j and the energy source k. The RCO consist of capital expenditures for vehicle $CapEx_{i,j,k}^{Inf}$ and for infrastructure $CapEx_{i,j,k}^{Veh}$, possible subsidies for vehicle and infrastructure $Sub_{i,j,k}^{Veh,Inf}$, operational expenditures for vehicle $OpEx_{i,j,k}^{Veh}$ and for infrastructure $OpEx_{i,j,k}^{Inf}$, possible tax advantages for vehicle $TB_{i,j,k}^{Veh}$ and resale value for vehicle $RV_{i,j,k}^{Veh}$.

$$RCO_{i,j,k} = (1+r)^h \cdot \left(CapEx_{i,j,k}^{Veh} + CapEx_{i,j,k}^{Inf} - Sub_{i,j,k}^{Veh,Inf}\right) + \sum_{t=1}^{h}\left((1+r)^{h-t} \cdot \left(OpEx(t)_{i,j,k}^{Veh} + OpEx(t)_{i,j,k}^{Inf}\right)\right) - TB(t)_{i,j,k}^{Veh} - RV(t)_{i,j,k}^{Veh} \quad (1)$$

The operational expenditures, possible tax advantages and resale value are dependent on the expected service period h of the simulation agents. The operational expenditures for vehicle can be divided into time-dependent and mileage-dependent expenditures. The mileage m dependent energy consumption costs for vehicle $EN_{i,j,k}^{Veh}$ are calculated from the specific energy consumption per km $spEN(m)_{i,j,k}^{Veh}$ and the energy price ENP^{EC}

$$EN_{i,j,k}^{Veh} = spEN_{i,j,k}^{Veh} \cdot ENP^{EC} \quad (2)$$

The specific energy consumption is calculated according to [10]. The energy price is calculated from the purchase price of energy carrier PP^{EC}, the CO_2 price of energy carrier CP^{EC} and the taxes for the energy carrier ET^{EC}.

$$ENP^{EC} = PP^{EC} \cdot CP^{EC} \cdot ET^{EC} \quad (3)$$

For fossil fuels, blending rates can be assumed, which influence the individual parameters depending on the blending of the reference fuel.

For the most cost-effective selection, the specific CO_2 consumption is compared with the applicable average CO_2 fleet limit values. If this is above the limit, a threshold in euros per g CO_2 is added to the investment costs. It is assumed that the penalty to be paid by the vehicle manufacturers in this case is passed on to the vehicle customer (simulation agent). The ranking after the RCO simulation is updated in this case until the minimum alternative is selected. The outputs from the market simulation are relative market shares, specific energy consumption and CO_2 emissions in km for all vehicles.

3.2 Vehicle stock modelling

The modelling of the vehicle stock is represented in an evolutionary model [11]. Based on historical vehicle stock statistics, future new vehicle registrations and de-registrations, the future vehicle stock is simulated. The historical stock is divided according to different registration years of the stock vehicle. The new registrations are based on the market volume forecast and the calculated market shares as described in chapter 3.1. Age- and mileage-based survival rates were determined from the deregistration figures [12].

$$stock_{i,j,k}^{sy,ry} = historical\ stock_{i,j,k}^{sy-1,ry-1} + new\ registration_{i,j,k}^{sy,ry} - deregistration_{i,j,k}^{sy,ry} \quad (4)$$

The vehicle stock data also include information on specific energy consumption and CO_2 emissions. For the simulated vehicles from 2020, the values come from the model approach in chapter 3.1. For the vehicles in the historical vehicle stock, the values from the Handbook for Emission Factors (HBEFA version 4.2) are used [13].

Greenhouse gas emissions from transportation are determined based on energy consumption in Germany [14]. Therefore, the territorial principle is applied for the balancing of energy consumption depending on the mileage. Here, the energy consumption of road freight transport is simulated based on the domestic mileage of road freight transport. The domestic mileage is composed of the total mileage of domestic and foreign vehicles within Germany. Based on the historical mileage data according to the registration ages, mileage regression rates are derived. Together with the mileage forecasts and the regression rates, the future mileage developments are calculated.

Energy consumption is calculated from the mileage and specific energy consumption. The downstream CO_2 emissions are calculated using energy carrier-specific emission factors. The emission factors are available on an annual basis. The emission factors for the reference fuels are calculated dynamically via the blending rate of synthetic fuels. The target value for the overall calculation is the mileage-related CO_2 emissions. The calculation of the new vehicle market is iterated until the CO_2 emission for the target year is reached. The overall model is technically implemented in the VECTO21 software structure [15].

3 Scenario definition and key assumption

External factors influencing the calculation are political regulations (such as CO_2 fleet regulation, purchase incentives, tax and toll exemptions), technology development influencing the vehicle efficiency and production capacities needed for the production unit dependent component costs as well as forecasts for the transport activities. These variables are subject to a certain uncertainty because the values have a wide range or their long-term development is unknown. The following table lists the main scenario measures for the three technology scenarios.

Table 1: Relevant scenario measures and assumptions for the three technology scenarios

Scenario measurements	**GHG-100_E-Fuels scenario**	**GHG-100_E-Mob scenario**	**GHG-100_H2 scenario**	**Source**
CO_2 Regulation framework				

(domestic) GHG emission reduction target compared to 1990	-100% until 2045	-100% until 2045	-100% until 2045	[5]
EU average CO2 emission targets LDV compared to 2020	2025: -15% (fixed); 2030: -55% (proposed); 2035: -80% (assumption); 2040: -100% (assumption)			[16, 17]
EU average CO2 emission targets HDV	2025: -15% (fixed); 2030: -30% (fixed); 2035: -65% (assumption); 2040: 100% (assumption)			[18]
Crediting of E-Fuel Blends in EU CO2 fleet emission regulation via CO2 certification trading	possible	Not possible	Not possible	[19]
(domestic) CO2 price	2020: 25€/ton CO2) until 2025: 65€/ton CO2 (fixed); 2030: 100 €/ton CO2 (assumption); 2040: 200 €/ton CO2 (assumption); 2045: 300 €/ton CO2 (assumption)			[20]
Assumption of market and transport development				
Forecast post 2020 annual new vehicle registration (German Vehicles)	2020: 295.204 vehicles; 2030: +10% compared to 2020 (assumption); 2050 +5% compared to 2030 (assumption)			[21]
Vehicle segment shares (German Vehicles))	3.5 t. GVW: 75%, 7.5 t. GVW: 7%, 12 t. GVW: 3%, 18 t. GVW: 2%, 26 t. GVW: 4%, 40 t. GVW: 9% (2020)			[21]
Average vehicle service time (German Vehicles))	3.5 t. GVW: 14y, 7.5 t. GVW: 27y, 12 t. GVW: 17y, 18 t. GVW: 14y, 26 t. GVW: 14y, 40 t. GVW: 7y (2020)			[21]
Forecast domestic vehicle mileage	2020: 83.5 billion veh-km; 2030: +10% compared to 2020 (assumption); 2050 +5% compared to 2030 (assumption			
Share of domestic heavy-duty vehicle mileage by foreign heavy-duty vehicles	9,5% (2020)			
Relevant technology cost degression				
Lithium-Ion Battery system	Initial price (2020): 168€/kWh Target price: 109€/kWh	Target price: 91€/kWh	Same as Ref. Scenario	[22]
Fuel Cell-System	Initial price (2020): 356€/kW Target price: 174€/kW	Same as Ref. Scenario	Target price: 121€/kW	[23]
H2-Tank-System (350bar)	Initial price (2020): 440€/kg Target price: 418€/kg	Same as Ref. Scenario	Target price: 322€/kg	[24]
H2-Tank-System (700bar)	Initial price (2020): 624€/kg Target price: 460€/kg	Same as Ref. Scenario	Target price: 416€/kg	[24]
Energy carrier's price development (without tax)				
Crude oil price	2020: 36€/bbl; 2025: 65€/bbl; 2030: 69€/bbl; 2040: 78€/bbl; 2050: 85€/bbl			[25]

Synthetic diesel (Ft-Diesel)	2020: 3,54€/l; 2030: 3,09€/l; 2050: 2,52€/l			[26]
Hydrogen price	2020: 6,64€/kg; 2030: 5,67€/kg; 2050: 4,71€/kg			[26]
Electricity end price	2020: 0,27€/kWh; 2030:0,30€/kWh; 2040: 0,30€/kWh			[27]
(other) Fiscal policy framework				
Vehicle tax (exemption)	Vehicle tax exemption for BEV and FCEV until 2030 (fixed)	Vehicle tax exemption for BEV until 2035 (assumption)	Vehicle tax exemption for FCEV until 2035 (assumption)	[28]
Energy tax (exemption)	Energy tax exemption for E-Fuels, Hydrogen and electricity until 2030, after like EU energy tax system (fixed)	Same as Ref. Scenario	Same as Ref. Scenario	[29, 30]
Purchase and infrastructure subsidies	Subsidies until 2025 for BEV and FCEV	FCEV same as REF, BEV toll subsidy until 2030	BEV same as REF, FCEV toll subsidy until 2030	[31, 32]
Toll (exemption)	Toll exemption until 2035 (assumption), after 50% until 2040, 100% after 2045 for BEV	FCEV same as REF, BEV toll exemption until 2040	BEV same as REF, FCEV toll exemption until 2040	[33]

4 Scenario results

This paper presents a scenario model to simulate the diffusion of alternative powertrains and energy carriers in the German road freight vehicle market. Three technology scenarios are described to achieve climate neutrality in road freight transport by 2045. These are E-fuels-, electric mobility- and hydrogen scenarios. The scenario assumptions are set in terms of pushing the respective technology into the market. The essential target criterion of the scenario analysis is the mileage-related CO_2 emissions of the stock fleet. In all three scenarios, CO_2 emissions of the road freight traffic are close to zero by the year 2045. The evaluation criteria are the market shares in new registrations, the domestic mileage and the final energy demand of German road freight transport. These differ between the individual scenarios and will be presented in the following for the presentation of scenario results.

5.1 Market potentials of alternative powertrains and energy carriers

Figure 2 shows the simulated market shares of alternative powertrains and synthetic fuels in the new registration vehicle market for each of the three technology scenarios plotted relative to each other. The figures are visualized in 10-year steps between 2030 and 2050. The market shares between 2020 and 2025 do not differ between the scenarios.

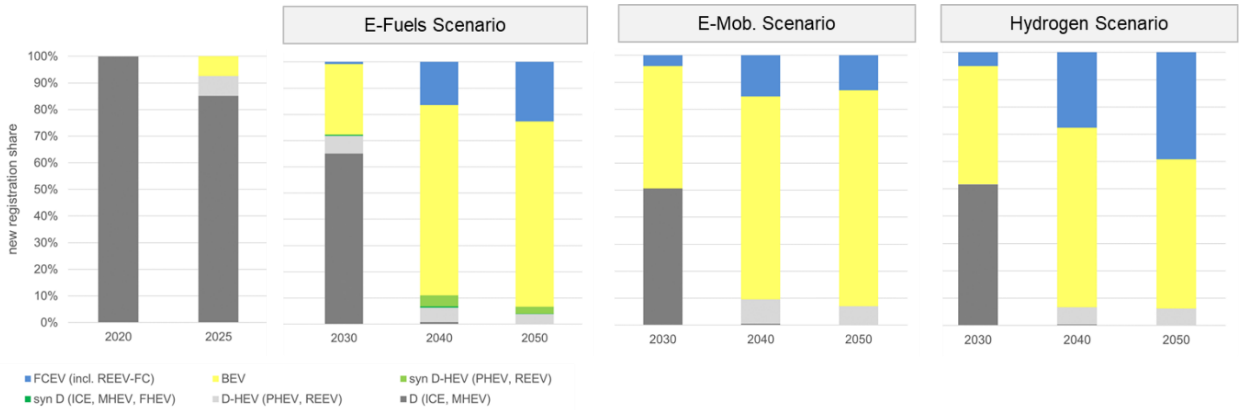

Figure 2: Simulated market shares of alternative powertrains and synthetic fuels for each technology scenario

In all three scenarios, the market share of BEVs increases rapidly from 2020 onwards, shaping up as the most dominant powertrain option after 2030. This is because, for the light commercial vehicle segment (gross vehicle weight below 3.5 tons), the BEV option penetrates the market without competition in all scenarios. Due to the large market volume of light commercial vehicles in the overall road freight market, a high BEV market share is illustrated. In the electric mobility scenario, BEVs also achieve market shares of over 50% within the heavy-duty vehicle segment after 2040. The market penetration of FCEVs initially takes place in the heavy-duty vehicle segment starting in 2027 and also in the LDV segment starting in 2035. However, the market shares differ strongly between the scenarios. In the hydrogen scenario, FCEVs reach a share of almost 50% within the heavy-duty vehicle segment in 2040, whereas within the light commercial vehicle segment the maximum market share is limited to 25% and is achieved only in 2050. E-fuels show no market potential in the electric mobility and hydrogen scenario, and low market potential in the e-fuels scenario. E-fuel potential is mainly seen in the heavy-duty vehicle segment. In the e-fuels scenario, the market shares for ICEs fueled by synthetic diesel (e-fuels) increase within the heavy-duty vehicle segment and reach a maximum of 15% in 2038.

5.2 Domestic mileage of road freight transport by energy carrier

Figure 3 shows the development of annual domestic mileage in vehicle kilometers of German road freight transport by different energy sources for each technology scenario. The figures are visualized in 10-year steps between 2020 and 2050. The yearly vehicle mileage between 2020 and 2025 does not differ between the scenarios. In all three scenarios, the electric mileage travelled can be seen to be steadily increasing. Indeed, the specific mileage in vehicle kilometers of heavy-duty vehicles is basically much higher than of light commercial vehicles. However, the total mileage of light commercial vehicles is higher than that of heavy-duty vehicles, due to the high market volume of light commercial vehicles. Since the evaluation of market shares in 5.1 shows a very high BEV share, this is also reflected in a high electricity-based mileage in road freight transport.

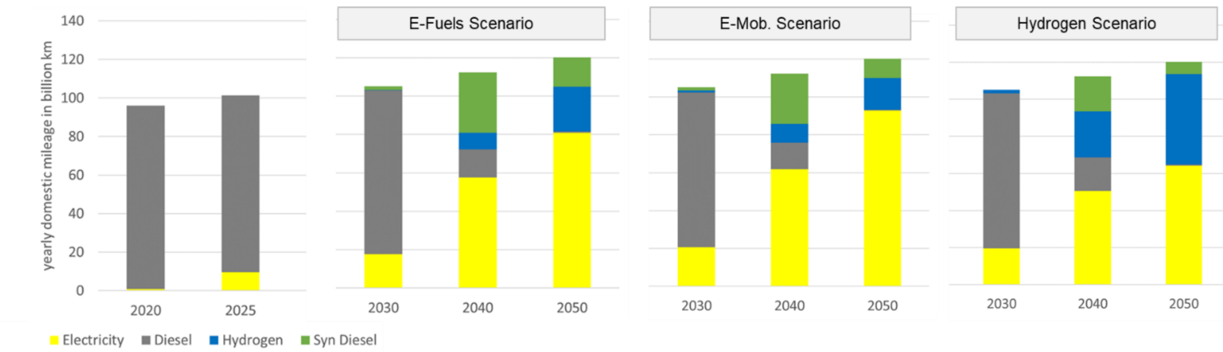

Figure 3: Development of domestic road freight transport performance by energy carriers for each technology scenario

For all three scenarios, the blending of synthetic diesel was assumed for the stock modelling. In the E-Fuel scenario, the blending rate for synthetic diesel is higher than in the other two scenarios. The synthetic diesel mileage increases sharply between 2030 and 2040, and levels off again after 2040, although the blending rate continues to increase. This is because only a small number of ICE trucks are sold after 2040 according to the scenario analysis. Thus, in the vehicle stock, their share decreases and so does the demand for fossil and synthetic fuels.

5.3 Energy demand of road freight transport

Figure 4 illustrates the final energy consumption of German road freight transport by energy source for each technology scenario. Again, the figures are shown in 10-year steps between 2020 and 2050. The distribution of annual final energy consumption by energy carriers between 2020 and 2025 does not differ between the scenarios. The yearly final energy consumption decreases significantly in all three technology scenarios. In the E-fuels scenario, final energy consumption decreases by about 29% until 2050 compared to 2005. In the hydrogen scenario, the yearly final energy consumption decreases by approx. 33.5% and in the electromobility scenario by approx. 36% compared to 2005. For all three scenarios, the energy consumption reduction is due to the steadily increasing share of more efficient powertrain options such as BEVs in the vehicle mileage.

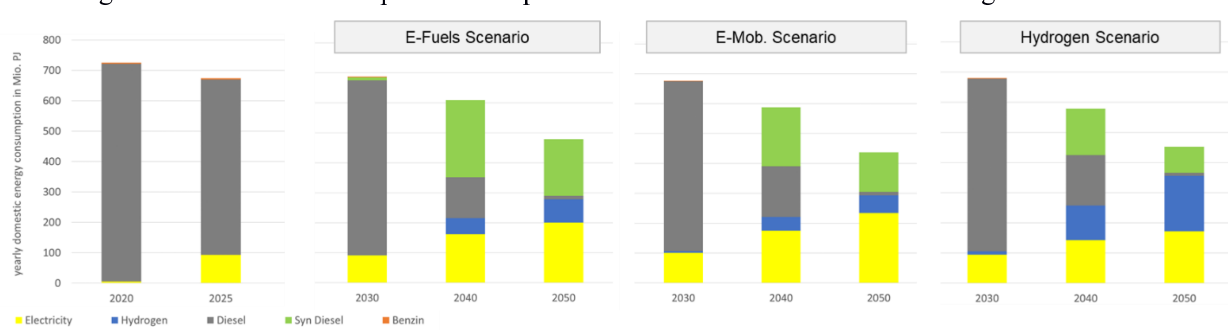

Figure 4: Development of yearly end energy consumption by energy carriers for each technology scenario

5 Discussion and Conclusion

The scenario analysis highlights that the direct electrification of vehicles predominantly shows the greatest market potential. At least for light commercial vehicles, BEVs are uncompetitive. In applications where direct electrification does not show any market potential, FCEV trucks are necessary, especially for heavy-duty vehicles on long-haul transport. E-fuels are particularly necessary for the decarbonization of the existing fleet. In the scenario analysis, an increasing blending in today's diesel fuel was assumed. On the other hand, the blending of synthetic fuels depends on the dynamics of fleet replacement. Rapid market penetration of BEVs reduces e-fuels demand. In principle, a cross-sectoral assessment of the energy challenge is necessary. On the one hand, to evaluate an efficient use of the energy used in the form of final energy carriers. On the other hand, to consider limitations emanating from the available amount of energy carriers for the transport sector. The German government's target of using electricity or electricity-based fuels to cover one-third of the mileage of heavy-duty traffic in 2030 will not be achieved in any of the three technology scenarios. Given an average service life of 10 years for trucks, a significant market share would already have to be achieved today. Another target defined by the German government for the transportation sector is to reduce final energy consumption by 40% by 2050 compared with 2005. The electromobility scenario clearly shows that energy savings of up to 36% are possible in German road freight transport, purely through technological measures. The technology scenarios thus make it clear that reduced final energy consumption and a switch to renewable and climate-neutral energy sources will not be necessary to decarbonize German road freight transport.

The scenario analysis presented shows a technological setup to decarbonize road freight transport. Shift potentials to rail or a structural change in the logistics sector accompanied by changes in mileage were not considered. However, pure technological transformation will not be sufficient to achieve the national and European climate protection targets for road freight transport.

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