StratES - Scenarios for the electrification of road freight transport

Study based on market ramp-up modeling

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Third report of the research and dialog project
"StratES: strategy for the electrification of road freight transport".

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AADT	Annual average daily traffic
AFIR	Alternative Fuels Infrastructure Regulation
BEHG	Fuel Emissions Trading Act (**B**rennstoff**e**missions**h**andels**g**esetz)
BEV	Battery electric vehicle
Ch	Charging
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CP	Charging point
ETS II	EU emissions trading system for buildings and transport
EU	European Union
HRS	Hydrogen refueling station
FCEV	Fuel cell electric vehicle
FT	Fuel tap
GHG	Greenhouse gas
GVW	Gross vehicle weight
HDV	Heavy-duty vehicle (from 3.5 tons gross vehicle weight)
H_2	Hydrogen
ICEV	Internal combustion engine vehicle
O-BEV	Overhead catenary battery electric vehicle
OC	Overhead catenary system
TCO	Total cost of ownership
TEMPS	Transport Emissions and Policy Scenarios (Model)
TREMOD	Transport Emission Model
TT	Tractor trailer
ZEV	Zero Emission Vehicle

Summary

There is an urgent need for action to reduce greenhouse gas emissions from road freight transport by transitioning to electric commercial vehicles.

Over the past 30 years, greenhouse gas emissions from road freight transport in Germany have increased by 30 % (UBA 2023b). The goal of climate neutrality in 2045 and the necessary reduction of CO_2 equivalents emitted in the entire transport sector by around half by 2030 require a rapid switch to climate-neutral transportation. Analogous to passenger cars, heavy-duty commercial vehicles are showing a transition towards electric vehicle propulsion. This transition is facilitated by advancements in battery technology and effective regulatory frameworks set forth by the European Union.

The objective of this study is to evaluate electric drive technologies in terms of their techno-economic potential and identify key factors influencing market adoption. The basis for this evaluation is the modeling of scenarios that encompass various technology mixes, energy price developments, and the expansion rates of public energy infrastructures. The analyses primarily focus on three technology pathways: (1) "BEV": battery electric trucks only, (2) "BEV + FCEV": a combination of battery electric trucks and fuel cell trucks, and (3) BEV + O-BEV: a combination of battery electric trucks and battery electric overhead catenary trucks.

In the future, the transport market will be primarily shaped by battery-electric heavy-duty vehicles, while fuel cell trucks and overhead catenary trucks show lower potential.

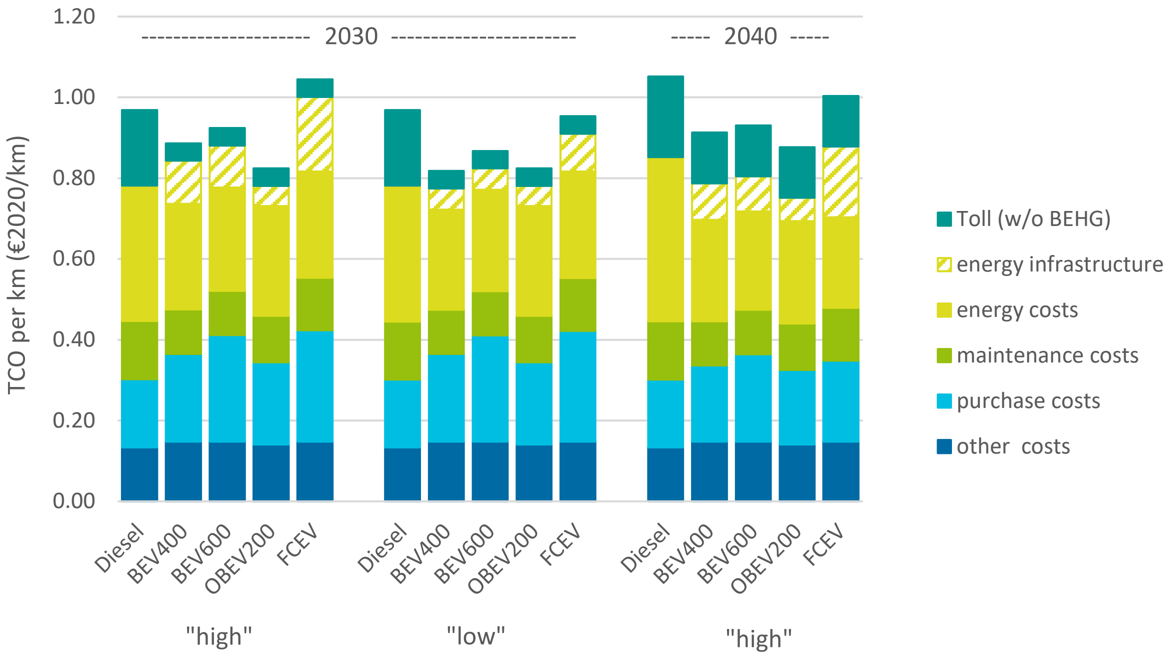
In the three technology pathways, battery electric trucks dominate the sales of zero-emission propulsion systems. The analysis considers the technical feasibility based on potential vehicle range and the availability of recharging options. The ramp-up of fuel cell trucks is more dependent on future energy price trends due to their higher energy consumption. Only in combination with optimistic price assumptions for climate-neutral hydrogen and high market prices at high power charging points will fuel cell trucks achieve significant market shares. At the same time, there are high uncertainties in the short and medium term regarding the price and availability of climate-neutral hydrogen at truck refueling stations. Overhead catenary trucks have favorable total costs of ownership in comparison among the propulsion technologies. However, the technical feasibility within the overhead infrastructure framework, as stipulated by an overhead network spanning approximately 4,000 kilometers in Germany, limits their market share to around one-third.

A CO_2-based truck toll and the availability of public energy supply infrastructures are the primary levers for the market uptake of electric heavy-duty vehicles.

The scenarios take into account the need for charging stations, hydrogen refueling stations and overhead catenary systems to operate the respective electric commercial vehicles. In addition to technical feasibility based on the availability of energy infrastructures, the total costs of ownership include an infrastructure fee to finance their establishment and operation. Two pricing scenarios are compared: one primarily cost-driven ("low") and another with a higher market price ("high") reflecting demand risks and supply shortages. Particularly in the second energy price scenario, a CO_2-based truck toll secures the cost advantage of emission-free propulsion systems as early as around the year 2030 (Figure 1-1). In the scenario calculations (in November 2022), it was assumed that a CO_2 surcharge of 200 euros per tonne of CO_2 would be introduced from 2024 and that the truck toll would be extended to all heavy-duty vehicles with a gross vehicle weight of 3.5 metric tons or more. Emission-free propulsion systems would receive a 75% reduction in infrastructure costs until 2030.

From 2031, the reduction would decrease to 50%. A largely consistent design is expected to be adopted by the German government in 2023.

Figure 1-1: Total cost of ownership (TCO) of powertrain options for two acquisition years and energy price scenarios ("high" and "low").



User profile: semitrailer tractor, 5-year holding period, 120,000 km annual mileage

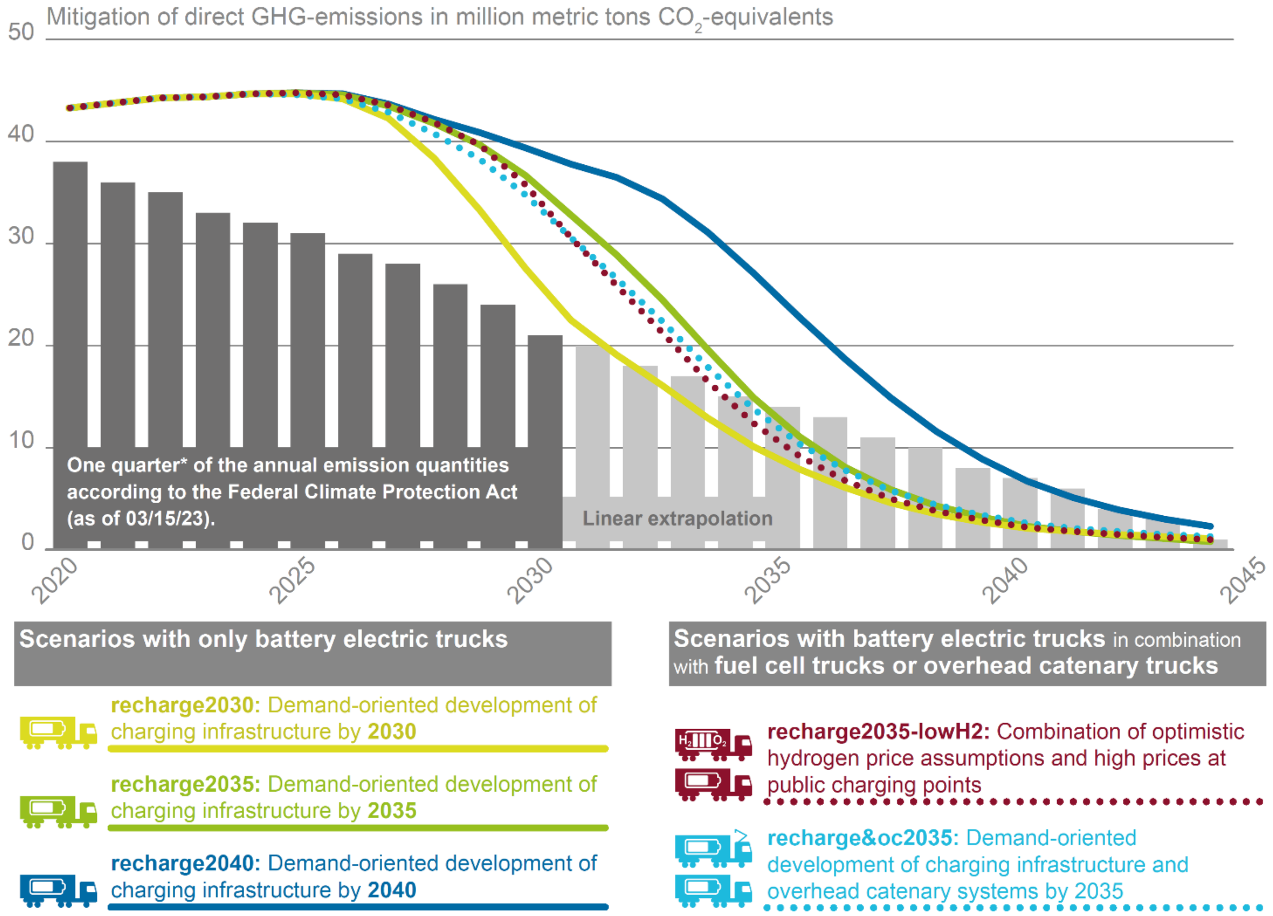
Source: Own calculations

The direct annual greenhouse gas emissions from road freight transport can achieve the set target trajectory as early as 2030 through a rapid electrification process.

In the scenarios with the previously described framework of a CO_2-based truck toll, the uptake of electric commercial vehicles primarily depends on the rate of expansion of public charging infrastructure. If a comprehensive and efficient charging network is available in 2035 ("recharge2035"), the modeling predicts that 100 % of new heavy-duty commercial vehicles will be emission-free in the following years (55 % in 2030). As a result, greenhouse gas emissions from road freight transport, particularly post-2030, are projected to drop to nearly zero by 2045 (Figure 1-2). If battery electric trucks can be deployed across all user profiles by 2030 ("recharge2030") due to the availability of appropriate charging infrastructure, their market share in new registrations is expected to reach 92% in 2030, driven by economic incentives.

In both scenarios, the share of new registrations for emission-free commercial vehicles exceeds both current and proposed minimum requirements set by the European Union within the context of CO_2 fleet limits. Furthermore, the demands for energy infrastructure surpass the designated minimum targets within the EU. National climate protection legislation and the articulated goals for road freight transport necessitate ambitions for the market uptake of electric heavy-duty vehicles and the development of energy infrastructures that go beyond the EU's framework.

Figure 1-2: Direct GHG emissions from road freight transport in the scenarios.



Road freight transport currently generates about a quarter of the transport sector's GHG emissions. To evaluate the GHG reductions in the scenarios, the annual emission volumes from KSG 2023 are therefore shown reduced by a factor of one quarter.

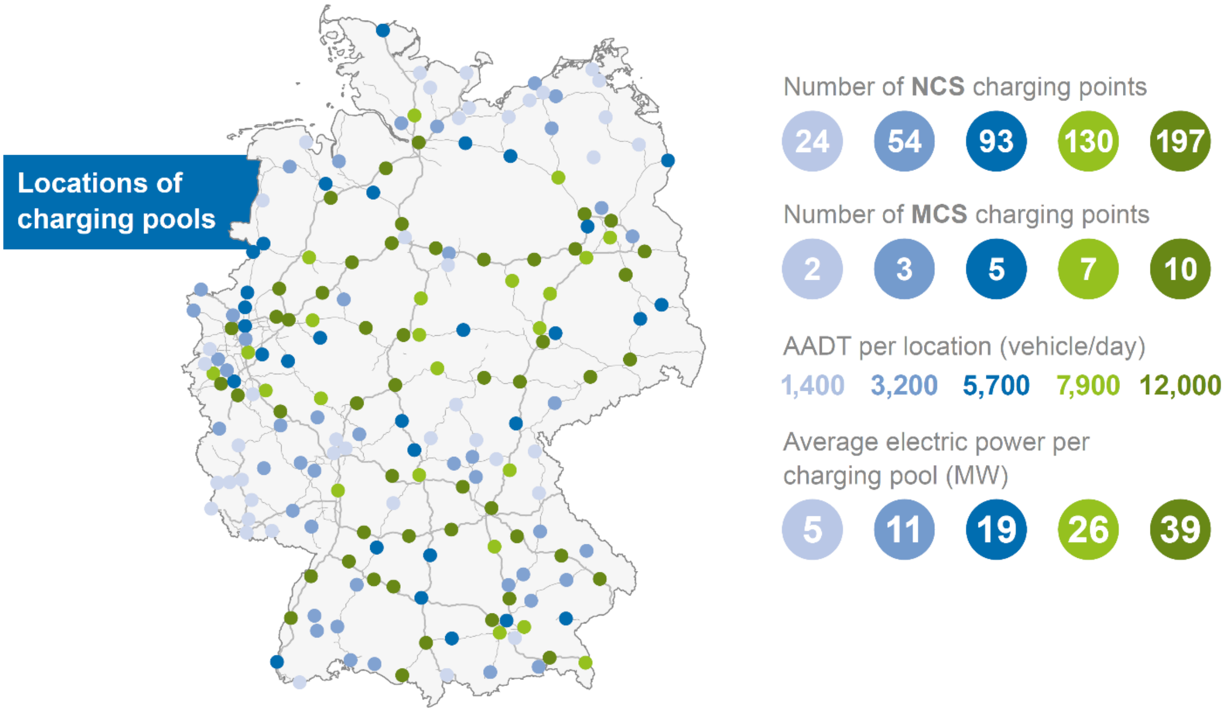
Source: Own calculations, UBA 2023b and KSG 2021

The establishment of energy infrastructures to support electric heavy-duty transportation requires early and targeted planning.

To estimate the required energy infrastructures, the modeled energy demand of road freight transport was allocated to regional traffic demand using a location grid. Different types of charging points were distinguished beforehand through route chain analysis. As a result, approximately 55% of the energy demand is expected to be covered at depot charging points. For public charging at Night Charging Systems (NCS) and Megawatt Charging Systems (MCS), there is a huge buildup demand until 2035.

The regional demands depicted in Figure 1-3 along the federal highway network sum up to a total of 2,000 MCS charging points and 40,000 NCS charging points. Due to the high power demand of MCS charging points, there is a need for planning-intensive and time-consuming connections to the high-voltage grid at many locations.

Figure 1-3: Demand for public charging points along the federal highway network in 2035 as a function of local traffic volume ("recharge2035").



NCS: Night Charging System, 150 kW rated power (of which 85 % average power) MCS: Megawatt Charging System, 1000 kW rated power (of which 85 % average power)

AADT: Annual average daily traffic

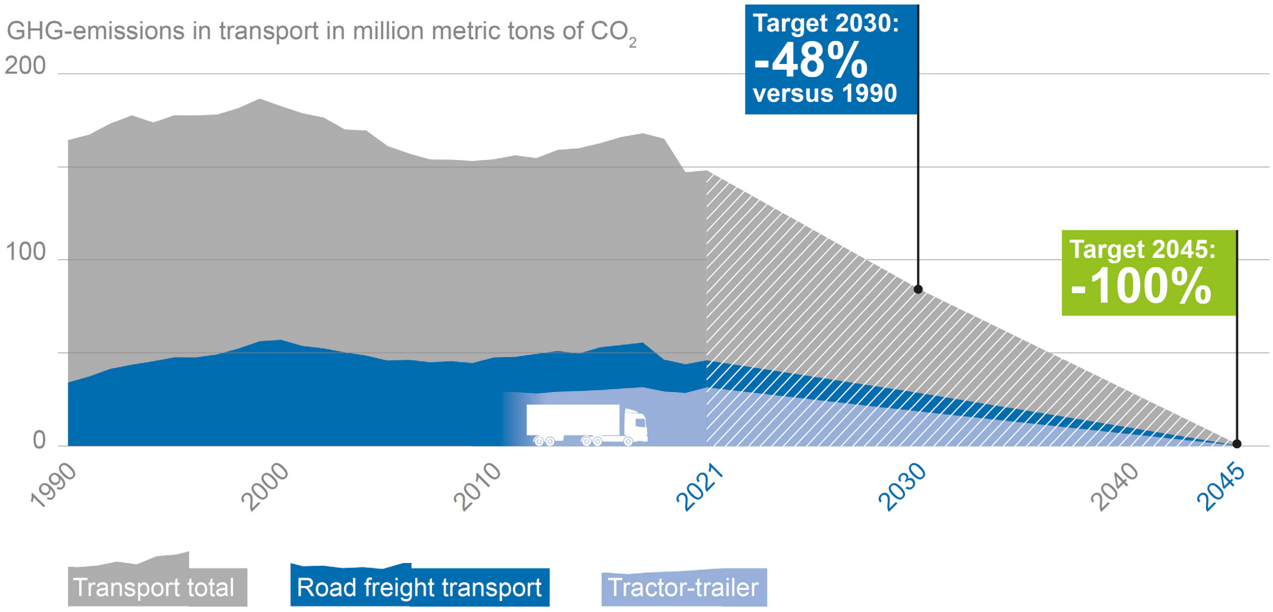
Source: Own calculations

1 Background and goals

In Germany, we cause around 20 % of greenhouse gas emissions (GHG emissions) through our mobility and transport in the transport sector. While overall GHG emissions decreased by 36% from 1990 to 2019, transport-related CO_2 equivalents were slightly higher than the 1990 level at approximately 165 million metric tons in 2019 (UBA 2023b). In road freight transport, GHG emissions actually increased by more than 30% over the same period due to increasing transport demand (UBA 2023b). The Covid19 pandemic led to a short-lived decrease in climate-damaging emissions, but this was mainly at the expense of mobility and goods transport. A systematic trend toward climate-neutral transport is urgently needed.

The National Climate Protection Act mandates a 48% reduction in GHG emissions for the transport sector by 2030 compared to 1990 levels (cf. Figure 1-1). Climate neutrality is to be achieved by 2045. In addition, Germany is obliged by the *Effort Sharing Regulation*[1] of the European Union to reduce GHG emissions by 50% in the period from 2005 to 2030. At the same time, the *Moving Long-Term Transport Forecast* commissioned by the German Federal Ministry of Digital Affairs and Transport (BMDV*)* assumes that transport volumes will continue to grow strongly. In the baseline forecast, the study predicts a 54% increase in road freight traffic between 2019 and 2051, and a 33% increase in rail freight traffic (Intraplan; Trimode 2023). Even with greater efforts to avoid traffic and shift to climate-friendly modes of transport, a switch to climate-neutral vehicle propulsion systems in road traffic is imperative.

Figure 1-1: Development of GHG emissions in road freight transport and mitigation targets in the transport sector



Source: Updated representation of Oeko-Institut; HHN; IAO; Intraplan 2020 on the basis of KSG 2021

Analogous to passenger cars, a trend toward electrification of the vehicle drive system is emerging for heavy-duty commercial vehicles. Boosted by technical advances in battery development and an effective regulatory framework set by the EU (cf. section 3), battery-electric trucks for regional

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[1] https://climate.ec.europa.eu/eu-action/effort-sharing-member-states-emission-targets_de

distances are already available on the market as series models in various configurations (cf. section 2.1). However, the majority of GHG emissions in road freight transport are emitted by trucks and tractor-trailers, which are mainly used for long-distance transport over long distances (cf. Figure 1-1). The BMDV is promoting three electric drive options that will have to prove themselves in regular use on long-distance routes in the coming years: (1) battery-electric commercial vehicles with recharging options at high-performance charging points, (2) fuel cell vehicles with hydrogen storage, and (3) commercial vehicles with retractable pantographs for dynamic power supply at overhead contact line installations that would be built on high-traffic highways (BMVI 2020).

Despite the remaining technical challenges of fleet electrification, manufacturers already expect high sales figures for electric drives in 2030. For commercial vehicles with a gross vehicle weight of 12 metric tons or more, manufacturers are forecasting a share of just under 58% for battery-electric drives in new registrations, and around 17% for fuel cell drives (NOW 2023). In 2021, the overall market share of electric drives in this size class was less than 0.2 % (cf. sec. 2.1). Some transport companies are still skeptical about electric vehicle drives and criticize the risk of possible payload losses and the lack of availability of energy supply infrastructures. (Oeko-Institut; Hochschule Heilbronn 2022).

The enormous time pressure to reduce GHG emissions from freight transport is illustrated by some scenarios that show transformation paths to climate neutrality. The study *Climate Neutral Germany 2045,* commissioned by the Climate Neutrality Foundation, Agora Energiewende, and Agora Verkehrswende, models new registration shares of electric trucks and semitrailers of just under 70 % for the year 2030 (Prognos; Oeko-Institut; Wuppertal Institut 2021). The studies *Climate Paths 2.0* by the Federation of German Industries (BDI) and the *Transport Target Paths* by Transport & Environment project even higher market shares of around 75 %, which would be necessary to achieve the national climate targets (BCG 2021; Prognos 2022). In the *long-term scenarios of* the German Federal Ministry of Economics and Climate Protection (BMWK), battery-electric heavy-duty vehicles including overhead line variants achieve a new registration share of 54 % in 2030 and 99 % in 2045. In this scenario favoring electromobility (*T45 electricity*), the existing fleet is not yet fully electrified in 2045 (Fraunhofer ISI; Consentec; ifeu; TU Berlin 2022).

In summary, a steep market ramp-up of electric commercial vehicles is required in the coming years in order to operate freight transport in a completely climate-neutral manner by 2045 in accordance with the targets set. It is therefore important to create the right framework conditions and prerequisites today to enable the transition to electric commercial vehicles.

Objectives of the study

Against the background outlined, the purpose of this study is to identify technology pathways and options for action for the complete electrification of road freight transport. Specifically, the following objectives are pursued:

- Development of technically and economically plausible technology pathways for the complete electrification of road freight transport by 2045.
- Consideration of three potential technology pathways: (1) pure battery electric, (2) a combination of battery electric drives and fuel cell drives, and (3) a combination of battery electric drives with and without a coupling option to overhead contact line systems.

- Model-based identification of key influencing variables and challenges for the respective technology pathways based on the market ramp-up scenarios.
- Assessment of demands for the development of energy infrastructures (charging points, hydrogen refueling stations, overhead catenary systems)
- Specification of the necessary framework conditions and need for action to enable a market ramp-up of promising technology pathways

This study forms the third report of the research and dialog project *StratES: Strategy for the Electrification of Road Freight Transport,* which is funded by the German Federal Ministry of Economics and Climate Protection (BMWK) as part of the *Renewably Mobile* funding program. The authors would like to expressly thank the project advisory board from industry, politics and science, which enriched the work with its expertise over a period of three years. In addition, discussions with various industry experts from the automotive, energy, and transportation industries were incorporated into the analyses.

The following chapter first provides a brief overview of the status quo of the market and technology of electric heavy-duty vehicles and the associated energy infrastructure. This is followed by a presentation of the most important legislation, particularly that of the EU, aimed at achieving greater climate protection in road freight transport. Based on this knowledge base, we present in chap. 4 in detail the methodologies, data and assumptions used in the market ramp-up modeling. Particular emphasis is placed on considering the range and associated deployment potential of electric commercial vehicles. In addition, various energy price scenarios will account for uncertainties in future price developments. Chapter 5 presents the results of market ramp-up modeling for the technology pathways studied and concludes with a balance of GHG emission reductions from fleet electrification. The demand assessment of the energy supply infrastructures required in the technology pathways is presented in Chapter 6. Finally, Chapter 7 summarizes the main conclusions of the analyses and recommendations for action on the electrification of road freight transport.

2 Status quo of market and technology

This chapter provides an overview of the status quo of zero-emission drive options for heavy-duty commercial vehicles. In particular, the market for battery electric trucks has seen dynamic developments in recent years. In addition, the further development of hydrogen-powered trucks and overhead catenary trucks is being driven forward by some manufacturers. In the following, the technical advantages and disadvantages of the vehicle technologies are first addressed and remaining technical challenges are highlighted. Subsequently, the status quo of the respective energy infrastructures - i.e. charging stations, hydrogen refueling stations and overhead line systems - will be shown.

2.1 Electric heavy-duty vehicles

Goods have so far been transported on the road almost exclusively by commercial vehicles with combustion engines for diesel fuels. Efforts to reduce GHG emissions from road freight transport have targeted alternative fuel concepts for many years. From today's perspective, the potential of approved biofuels is insufficient to fully power commercial vehicle fleets by 2045 (cf. IFEU; IZES; ÖI 2019 and Oeko-Institut 2020b). Synthetic fuels based on renewable electricity are not economically competitive for transport companies due to the costly and energy-intensive production chains (cf. e.g. Oeko-Institut 2021). For a few years now, political and industrial strategies have therefore been focusing on the electrification of commercial vehicle fleets, as is already established for passenger cars (BMVI 2020; NOW 2023).

The advantage of electric vehicle drives is their efficiency in converting electricity into drive energy with only low losses of 5-10 %. Internal combustion engines lose around 50-60 % of the energy used in the form of heat. In addition, the electric motor can act as a generator and recover energy during braking or downhill driving. So-called recuperation offers further potential for energy savings, especially in local and regional transportation. The disadvantage of electric vehicle propulsion is the energy storage systems, which have greater weights and volumes than liquid diesel fuel. This results in limited vehicle ranges compared with conventional commercial vehicles, as well as potential losses in payload or transport volume. The three electric drive options presented below pose individual challenges due to the different energy storage systems.

Battery electric drive

The enormous progress made in the development of lithium-ion batteries[2] currently already enables ranges of heavy commercial vehicles of around 300 km without significant losses in payload. For the payload trade-off, it is important to consider that the CO_2 emissions standards allow an additional weight of 2 tons for zero-emission powertrains (Regulation (EU) 2019/1242 2019). In addition, there are savings in the powertrain and fuel tank of 1-2 tons. The specific energy weight of the battery system is currently about 160 kWh/t and is expected to increase to 240-270 kWh/t by 2030 (Oeko-Institut; HHN 2020). In addition, efficiency gains via aerodynamic improvements, electric drive axles or electric trailers can increase the range. The ICCT forecasts ranges of 500 km for semitrailer trucks in 2030 without significant payload losses. (ICCT 2021b). At the same time, announcements by manufacturers promise long-distance BEVs with significantly increased ranges in the coming years.

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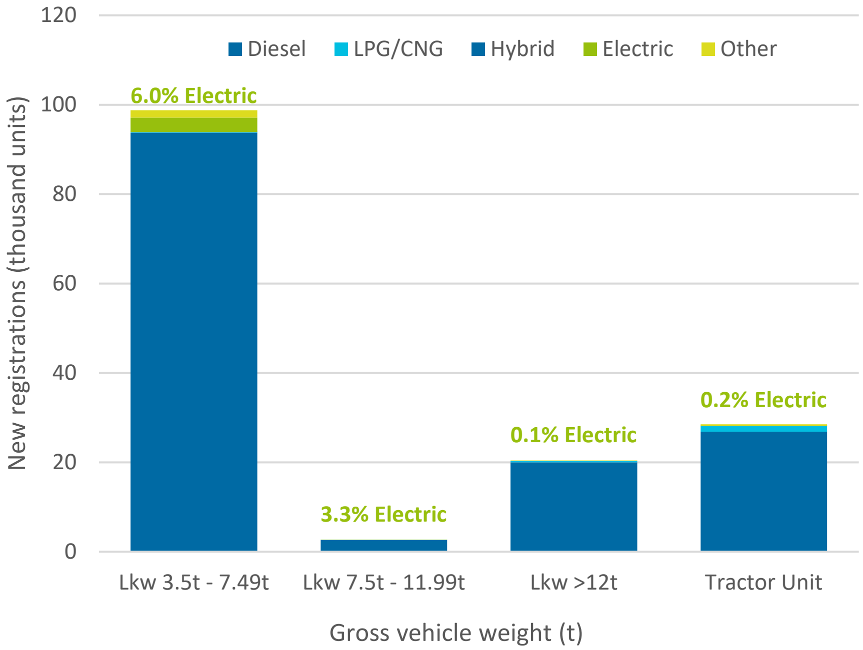
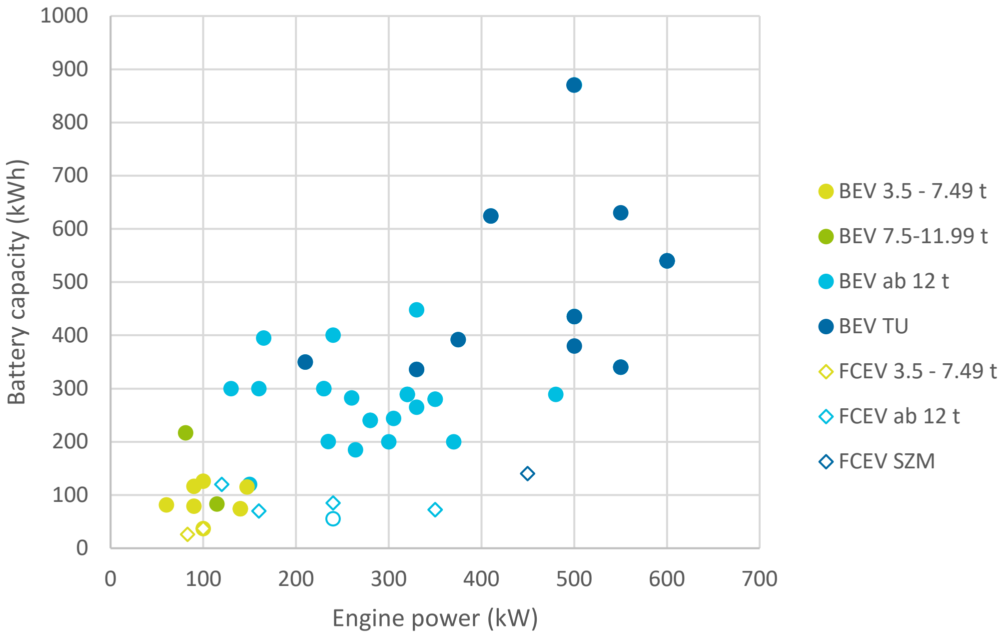
[2] An overview of the development of the energy density of battery cells is provided by e.g. Fraunhofer ISI 2022

Figure 2-1: **New registrations of heavy commercial vehicles in 2021 by size class and drive system**



Source: Own calculations based on KBA 2022

Figure 2-2: **Overview of battery capacities of available vehicle models in the segment of electric heavy-duty vehicles**



Source: Own representation based on www.my-e-roads.de

In new registrations, BEVs for the size class from 3.5 to 7.49 t total weight will already achieve visible shares of around 3% in 2021 (Figure 2-1). For the remaining trucks and tractor units, the share of BEVs in new registrations is less than 0.2%. The supply of heavy-duty trucks in the EU is mainly determined by five major manufacturers and their associated brands: Daimler Truck (including Mercedes Benz), Traton Group (MAN and Scania), Volvo Group (including Renault), PACCAR (DAF) and CNH Industrial (Iveco). In addition to the above-mentioned manufacturers, several other companies, such as Designwerk, E-Force or Quantron, offer battery-electric models in various vehicle configurations and battery capacities. An overview of available vehicle models is provided by the *My eRoads* platform[3] , which is illustrated in Figure 2-2. The majority of current vehicle models have battery capacities of less than 500 kWh.

For use in long-distance transport with daily mileages of up to 1000 km, BEVs will in all likelihood require an additional energy supply also in the future. The megawatt charging standard should enable the battery to be recharged within the legally prescribed driving and rest breaks. In this case, the battery storage can be dimensioned for the maximum distance of around 400 km that can be driven in 4.5 hours. However, only prototypes of the megawatt charging standard exist to date, and the vehicles are also limited to a power consumption within the available CCS charging standard of up to 350 kW. Key technical challenges for battery-electric commercial vehicles include increasing the charging power, cycle stability during frequent charging processes and the service life of the battery system.

Further risks are the costs for the battery system, which also entail higher purchase prices for BEVs in a mass market compared with conventional diesel vehicles. Due to the energy savings, BEVs nevertheless offer high economic potential. The consultancy *PwC* estimates that BEVs will account for at least half of truck production in Europe, North America and China in 2035 (PwC 2022). The *IEA*'s *Global Electric Vehicle Outlook* forecasts that electric commercial vehicles will account for 7-30% of new global registrations by 2030, depending on political actions (IEA 2022). In Germany, manufacturers assume new vehicle registration shares of around 60 % in 2030 (NOW 2023)..

The challenge for transport companies is to integrate BEVs into regular operation. The limited range and charging times compared to diesel trucks must be taken into account in route planning. There is still skepticism on the part of transport companies, especially with regard to long-distance transport, which can only be overcome once the vehicles have proven themselves in everyday use. (Oeko-Institut; Hochschule Heilbronn 2022).

Hydrogen fuel cell drives

In fuel cell electric vehicles (FCEVs), the fuel cell converts hydrogen into electricity for the electric powertrain. The fuel cell is designed for about half the engine power. FCEVs therefore have an additional battery system to absorb peak loads and recuperation energy. Compared to BEVs, this is smaller in size. The current vehicle models in Figure 2-2 have battery capacities of up to 140 kWh.

In terms of mass, hydrogen is an effective energy store. At 120 MJ/kg, its calorific value is almost three times higher than that of diesel fuels (43 MJ/kg). However, hydrogen is the lightest element in the periodic table. Therefore, hydrogen is volatile and must be highly compressed or liquefied for practical storage volumes. Steel tanks overcompensate for the mass advantage of hydrogen. The specific gravity of a hydrogen tank at a pressure of 700 bar is about 100-200 kWh/t and that of a

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[3] https://www.my-e-roads.de/de-DE/export/fahrzeuge

tank for liquid hydrogen is 200-400 kWh/t (Sartbaeva et al. 2008). Space behind the driver's cab is required to accommodate all components in addition to the chassis.

The range of available heavy commercial vehicles with fuel cells is around 400 km with a hydrogen tank of 32 kg capacity. The storage pressure of gaseous hydrogen is still limited to 350 bar for current commercial vehicle models. If the storage pressure is increased to 700 bar, as in the passenger car segment, the range will double. Although uncertainties remain about the future state of aggregation and the storage pressure in the tank due to different announcements by manufacturers, according to current knowledge, ranges of 800-1000 km seem realistically achievable in 2030.

Due to the range potential, the hopes of many transportation companies lie in hydrogen-based drives. In addition to fuel cells, the hydrogen internal combustion engine is also seen as having high market potential (Oeko-Institut; Hochschule Heilbronn 2022). However, the operation of the hydrogen combustion engine is not emission-free, since nitrogen oxides are produced by the combustion process and the partially required supporting combustion with diesel fuel leads to further air pollutant and greenhouse gas emissions.

Losses of at least 40 % occur during energy conversion in the fuel cell. The efficiency of FCEVs is consequently significantly worse than that of BEVs. The hydrogen combustion engine is even less efficient than diesel engines (Hosseini and Butler 2020). Savings in operating costs for FCEVs therefore depend heavily on hydrogen prices at refueling stations. Projected purchase prices for FCEVs are also higher than the prices of established diesel trucks in the medium term. Based on the economic potential, *PwC* estimates the market share of fuel cell heavy-duty vehicles in 2035 to be around 10-15% in Europe, North America and China (PwC 2022). A meta-study by the International Transport Forum shows that studies for FCEVs only calculate market shares in conjunction with very favorable assumptions for hydrogen (ITF 2022). In Germany, manufacturers expect a market share of 17% of new registrations in 2030 (NOW 2023).

Almost all commercial vehicle manufacturers are active in the further technical development of FCEVs. In addition to available models of heavy trucks and tractor units from Hyundai, Hyzon and Faun, Daimler Truck, among others, has announced a long-range production model for the second half of the decade. By next year, Iveco plans to market the fuel cell truck developed in cooperation with Nikola through the rental company Hylane[4] , among others. As the overview in Figure 2-2 makes clear, BEVs currently have a technological lead over FCEVs. In local and regional transport, BEVs are considered to be a set technology for future fleets, as is the case in the passenger car segment. (BMVI 2020). The question remains open as to whether BEVs will prove practical in long-distance traffic or whether FCEVs will be able to gain market share in these application profiles.

Technical challenges for the further development of fuel cell trucks exist in temperature management, the purity requirements of the fuel cell for the hydrogen, a further reduction of the platinum content in the fuel cell, and the further development of hydrogen storage technology. In addition, there are significant challenges for the supply of climate-neutral hydrogen, which are discussed in connection with refueling stations in Sect. 2.2 are discussed.

Overhead catenary drive

Another option for supplying power to the vehicle is to provide propulsion energy directly from overhead contact line systems installed on the roadway, as is common for rail vehicles and applied

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[4] https://www.hylane.de/

to some city buses (Boltze et al. 2021). In this case, the vehicles are equipped with an automatic extendible and retractable pantograph. Depending on the availability of electrified lines, this allows the energy storage in the vehicle to be smaller. Catenary-capable battery electric vehicles (O-BEVs) have the further advantage that the battery system can be charged dynamically while the vehicle is in motion, thus avoiding or reducing standstill times for recharging.

To date, a few prototypes exist that are being used in three field trials in Germany (ELISA[5], FESH[6], eWayBW[7]). The tractor units are hybrid models equipped with an additional diesel engine. The battery size has been increased to 74 kWh in the current third configuration to allow longer emission-free trips beyond the overhead system (Oeko-Institut; IFEU; Fraunhofer ISI 2022). The power of the electric motor totals 260 kW, while the combustion engine is rated at 330 kW. This year will also see the first deployment of an all-electric model (O-BEV).

Overhead contact line technology is being driven forward by Siemens. In cooperation with Continental, efforts are being made to optimize the pantograph and turn it into a component suitable for series production (ELONSO[8]). Scania is currently the only manufacturer active in vehicle development. Volvo was also involved in earlier practical trials. The manufacturers' sales forecasts do not include O-BEVs (NOW 2023). According to a survey of transport companies, the technology is not considered to have any market potential in 2030 (Oeko-Institut; Hochschule Heilbronn 2022). The companies involved in the field trials, on the other hand, are positive about their practical experience.

The efficiency of O-BEV is slightly lower than BEV due to the additional flow resistance of the extended pantograph. The vehicle costs are determined by the costs for the pantograph and the battery system and, depending on the battery size, can be lower than for BEVs. Accordingly, various studies assign high techno-economic potentials to O-BEVs (a.o. Oeko-Institut; IFEU; Fraunhofer ISI 2020, SRF 2020 or Oeko-Institut 2019).

In addition to power supply via overhead contact line systems, other technologies are being tested in Sweden and other countries under the general term *Electric Road Systems.* For example, electrical contact can be established on the ground via conductor rails in the roadway and current collectors under the vehicle, or contact-free via inductive systems (e.g. ElonRoad[9], Electreon[10]). The main advantage of the ground-based system is the ability to dynamically power additional types of vehicles, such as passenger cars. The disadvantage is the interaction with the highly stressed road materials, which is not yet conclusively known, and the resulting additional maintenance effort. Compared with conductive power transmission, inductive power transmission is more lossy. Therefore, as things stand today, the power consumption in the vehicle is not sufficient for regular operation. Of the Electric Road Systems outlined, the overhead contact line system is the most technically mature (WSP; ifeu; ÖI; Fraunhofer ISI 2022).

Technical challenges remain in the further development of O-BEVs into a production model, the integration of dynamic power supply into the power electronics of BEVs, the realization of charging

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[5] https://www.erneuerbar-mobil.de/projekte/elisa-ii-b and https://www.erneuerbar-mobil.de/projekte/elisa-iii
[6] https://www.erneuerbar-mobil.de/projekte/fesh-ii and https://www.erneuerbar-mobil.de/projekte/fesh-ii-b
[7] https://www.erneuerbar-mobil.de/projekte/ewaybw-ii
[8] https://www.erneuerbar-mobil.de/projekte/elonso
[9] https://elonroad.com/
[10] https://electreon.com/

powers in the order of 150 kW via the pantograph, and the optimization of the pantograph for series production.

2.2 Alternative energy infrastructures

The corresponding infrastructures must be built for the energy supply of electric heavy-duty vehicles. For all three electric drive options discussed above, no publicly accessible energy infrastructure exists to date. For classification purposes, comparisons with energy infrastructures for passenger cars and light commercial vehicles are listed below.

Charging stations

The development of publicly accessible charging infrastructure for passenger cars is being driven forward by various companies from the energy and petroleum industries as well as the automotive industry. According to the German Federal Network Agency, almost 70,000 normal charging points with a charging capacity of up to 22 kW and around 13,000 fast charging points are already in operation. A good half of the fast charging points are *High Power Charging (HPC)* charging points with charging capacities of 150 kW and above. (BNetzA 2023).

So far, there is no public charging infrastructure dedicated to heavy-duty vehicles. The BEVs already in operation by transport companies are charged in the depot. While the available *Combined Charging System (CCS)* charging standard allows charging powers of up to 350 kW in principle, many vehicle models are still limited to significantly lower charging powers. Today, battery storage for heavy commercial vehicles is already a factor of five larger than for passenger cars; in the future, battery capacities are likely to increase tenfold. The power requirement at the charging station is correspondingly higher.

In the CharIN initiative[11], industrial companies are therefore developing the *Megawatt Charging System (MCS)* charging standard, which, with charging powers of over one megawatt, is intended to enable large battery systems to be fully charged in 30-45 min. The technical challenges lie in the transmission of power to the vehicle. The high power output requires complex cooling of the connector via liquid heat transfer media. The market launch of the high-power charging points is scheduled for 2024. In the *HoLa* project - *high-performance charging in long-distance truck traffic*[12], the construction of two MCS charging stations along the A2 federal highway between Dortmund and Berlin is planned by 2025.

Three of Europe's largest commercial vehicle manufacturers - Daimler Truck, Traton Group and Volvo Group - have founded the joint venture Milence[13] to jointly advance the development of high-performance charging stations for heavy commercial vehicles in Europe. The aim is to establish around 1,700 high-performance charging points for trucks in Europe by 2027.

In addition to the interface between the vehicle and the charging station, there is a need for development in the integration of the charging infrastructure into the power grid. Whereas a connection to the medium-voltage grid has generally been sufficient for public charging hubs in the passenger car segment to date, studies for truck charging hubs assume that a connection to the high-voltage grid is required (NOW 2022a). In addition, further developments of power or charging

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[11] https://www.charin.global/
[12] https://hochleistungsladen-lkw.de/hola-de/projekt/
[13] https://milence.com/

management systems are required to effectively cushion peak loads. Potential for feeding energy stored in the battery systems back into the power grid via bidirectional charging systems is also likely to come increasingly into focus for heavy commercial vehicles.

Hydrogen refueling stations

The construction and operation of hydrogen filling stations in Germany is mainly carried out by the company H_2 Mobility[14], which was founded by the companies Air Liquide, Daimler, Linde, OMV, Shell and Total Energies. There are currently almost 100 hydrogen refueling stations for passenger cars and light commercial vehicles in operation. At some sites, refueling of buses and medium-duty commercial vehicles is possible at a storage pressure of 350 bar. The sites are concentrated in metropolitan areas and main traffic arteries, although the refueling stations are generally not located directly on the highway.

The maximum capacity of the filling stations so far is 0.5 tons of hydrogen per day. The aim is to build larger refueling stations with capacities of 4 tons per day, which can also be used by heavy-duty commercial vehicles. (H2 MOBILITY 2021). Depending on the storage technology, hydrogen storage requires a large amount of space. In the scale currently realized for passenger cars, H_2 Mobility indicates space requirements of 200 to 350 m^2. So far, delivery has been mainly by road using gas trailers and, for some stations, liquid gas trailers.

The main components of a filling station system for gaseous hydrogen consist of a basic storage tank at 200 to 250 bar, high-pressure intermediate storage tanks at 700 bar (or 350 bar) and gas compressors connected in between. Before refueling, the hydrogen is cooled to -40 °C so that the heating that occurs during the expansion from prepressure to tank pressure does not lead to critical temperatures in the vehicle tank. The refueling process is technically complex. Standardizations for refueling heavy commercial vehicles with gaseous hydrogen are being developed in the EU-funded project PRHYDE[15], among others. Currently, the refueling stations are still susceptible to maintenance and require improved reliability (CAM 2020).

There is also a need for development in gas compressors. For passenger cars, the capacity range is around 60 kg/h. The refueling of heavy commercial vehicles with 50 to 70 kg of hydrogen within 10-20 min requires gas compressors with higher performance, which are still under development. In addition, fuel cells have high purity requirements. Therefore, compression free of lubricants or a downstream purification stage is required.

There is not yet an established market for supplying filling stations with climate-neutral hydrogen. According to its website, H_2 Mobility obtains certified green hydrogen in part from the Netherlands. The majority of hydrogen is produced from fossil sources. Possible supply paths for the future supply of climate-neutral hydrogen are discussed, also with a view to cost structures, in Sect. 4.7.

Overhead catenary systems

The development of overhead contact line systems for road traffic is being driven forward by Siemens. Two contact wires are stretched over the road via masts and supplied with power from substations. While in trains the metallic contact between wheels and rail serves for grounding, in the road version the second contact wire acts as a second pole (Boltze et al. 2021). For city buses,

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[14] https://h2-mobility.de

[15] https://cordis.europa.eu/project/id/874997/de

overhead contact line systems are an established technology used in many cities, especially in Eastern Europe. The application for the operation of heavy commercial vehicles on highways is not yet in regular use.

In Germany, overhead contact line systems have been installed in three field trials on several kilometers of federal highways and roads in Hessen, Schleswig-Holstein and Baden-Württemberg. Prior to this, test tracks have been set up in public road space in California, USA and Sweden (Siemens AG 2017). In Sweden, a permanent line is to be electrified by 2025 (WSP; ifeu; ÖI 2023). Pilot projects in regular road operation have also been announced in France. In both cases, however, it remains to be seen whether overhead contact line systems or other *Electric Road Systems* technologies (cf. sec. 2.1) will be used.

Activities are underway at European and national level to standardize the technologies, for example, to standardize the interfaces between the vehicle and the pantograph and between the pantograph and the overhead contact line. In this context, regulations of vehicle construction meet rail-related standards (Oeko-Institut; IFEU; Fraunhofer ISI 2022).

In 2021, the German government announced that it would promote innovation clusters for heavy-duty transport in order to test electric technology options on a larger scale in regular use (BMVI 2021). Two of these innovation corridors were to include longer test routes for overhead contact line systems in Hessen / Baden-Württemberg and Bavaria. Since then, however, there has been no concretization. Feasibility studies recommend electrifying about one-third of the German highway network (about 4,000 km) using overhead lines to provide potential power supply via overhead lines for about two-thirds of the heavy-haul traffic (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020).

The power supply of heavy commercial vehicles via overhead contact line systems has been demonstrated in principle. However, further development is required for scaling up to longer sections and a potential overhead contact line core network on the main arteries of the federal highway network. For example, to drive a larger consecutive number of articulated trucks, the voltage level of the overhead line system must be significantly increased from the current 600 V (Oeko-Institut; IFEU; Fraunhofer ISI 2022). In addition, billing systems for electricity purchases must be developed (IKEM 2022 , ICEM 2020).

3 Regulatory framework

This chapter presents the European and national legislation that sets the framework for the electrification of commercial vehicle fleets. At the EU level in particular, key policies have come into force in recent years that represent significant drivers for climate protection in road freight transport. Of particular note are the proposed 2023 revision of CO_2 emission standards for heavy-duty vehicles, the Eurovignette Directive amended in 2022, and the regulation on the deployment of alternative fuels infrastructures adopted in 2023.

This is followed by a brief presentation of the climate protection legislation in force at national level and the policy measures implemented to date. The policy instruments listed in this chapter provide the framework for the market ramp-up modeling. They also provide the basis for design options in the scenarios developed.

3.1 CO_2-emission standards for heavy-duty vehicles

With the CO_2 emission standards for heavy-duty vehicles, EU-wide binding fleet target values for this vehicle class came into force for the first time in 2019 (Regulation (EU) 2019/1242 2019). This requires manufacturers to reduce the CO_2 emissions of their new vehicle fleets by a specified reduction compared to a reference value. The regulation is cited by manufacturers as a key driver for the transition to electric vehicle drive systems in heavy-duty transport (Oeko-Institut; HHN 2020).

The revision proposed by the EU Commission in February of this year[16] further increases the level of ambition. Up to now, only certain commercial vehicle classes with a gross weight of 16 metric tons or more have been regulated, which together account for 65% to 70% of CO_2 emissions from heavy commercial vehicles. The amendment provides for the scope to be extended to vehicle groups of 5 tons or more gross weight (including buses). In addition, trailers (trailers and semi-trailers) will be assigned reduction targets. Vehicles for special purposes, for example for public safety, medical care, but also vocational vehicles such as concrete mixers or excavators, remain exempt from regulation.

For the vehicle groups already regulated, a reduction of 15% compared with the 2020 reference value will apply from 2025. For 2030, the EU Commission proposes an increase in the reduction target from 30% to 45%. The same reduction target is to apply to newly regulated vehicles compared to a reference value to be determined in 2025. The proposed revision also updates the reduction targets to 2040, with a 65% reduction to apply from 2035 and 90% from 2040. A simplified illustration of the valid and proposed reduction targets is shown below in Figure 3-1.

The CO_2 emission standards are based on the energy consumption and CO_2 emission values determined with the VECTO[17] simulation tool during registration, which have been mandatory since January 2019 and must be collected during the registration process[18] and forwarded to the EU

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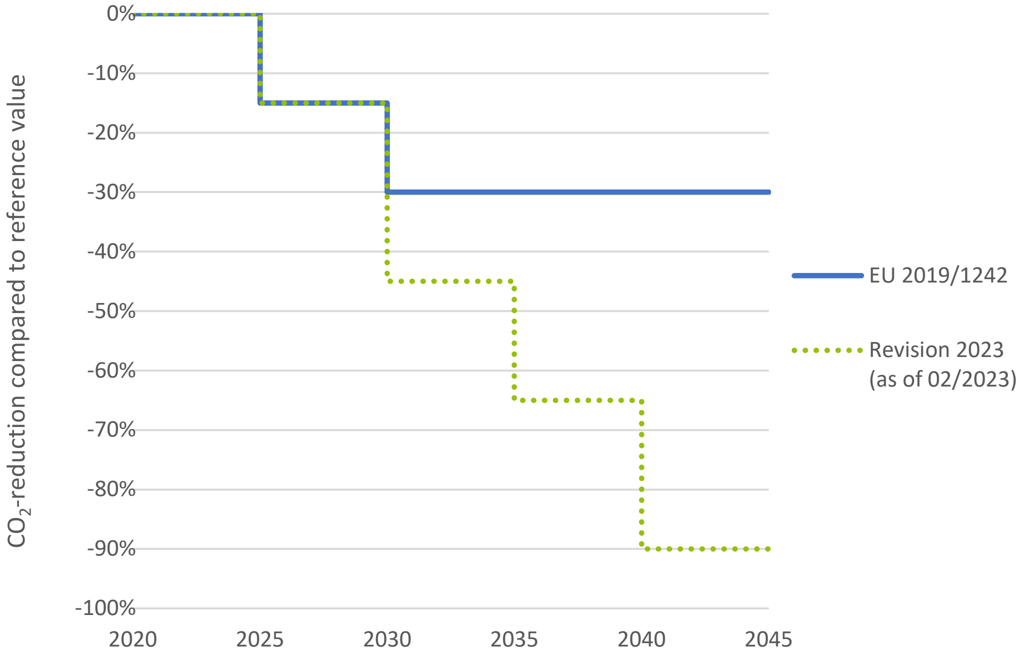
[16] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/1242 as regards strengthening the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, and repealing Regulation (EU) 2018/956. COM/2023/88 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A88%3AFIN

[17] https://ec.europa.eu/clima/policies/transport/vehicles/vecto_en

[18] EU regulation 2017/2400, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593438504238&uri=CELEX:32017R2400

Commission[19]. Essential for the calculation of CO_2 emissions with VECTO is the type of application profile (e.g. urban delivery or long-haul delivery), for which different mileages and payloads are assumed for the different vehicle groups. In addition, weighting factors are used to calculate the specific CO_2 emissions per new vehicle fleet of a manufacturer, which gives vehicle groups used in high-emission long-distance transport a high significance for meeting the target.

Figure 3-1: Illustration of CO_2 reduction targets of new heavy-duty vehicle fleets in the current Regulation EU 2019/1242 and the revision proposal.



Source: Own representation based on EU 2019/1242 and COM/2023/88.

A good overview of other mechanisms in the current regulation, e.g., for crediting emissions credits and debits, is provided by the ICCT (ICCT 2021a, ICCT 2019). In the proposal for revision, further mechanisms, such as the possibility of transfers between producers or exemptions for smaller companies, are considered. The consideration of direct CO_2 emissions per tonne-kilometer caused during operation remains binding. Furthermore, there are no plans to include climate-neutral fuels in the reduction targets, as they do not represent an economically viable alternative to electric drives. (European Commission (EC) 2023).

If manufacturers fail to meet the targets, they will be subject to high fines of €4,250 per gram of CO_2 per tonne-kilometer. The manufacturers' announcements in the BMDV's *cleanroom talks* already go well beyond the newly proposed targets for 2030: for example, the forecast share of new registrations of zero-emission commercial vehicles over 12 metric tons gross weight in Europe is 53% for BEVs and 10% for FCEVs. (NOW 2023). In total, this corresponds to a CO_2 reduction of 63 % in the new vehicle fleets through the new registrations of zero-emission drives alone, i.e. without additional consideration of potential efficiency improvements of new commercial vehicles with diesel

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[19] EU regulation 2018/956, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593438546703&uri=CELEX:32018R0956

combustion engines. Indeed, manufacturers assume only moderate improvements of diesel-powered vehicles of 5-10% by 2030 (Oeko-Institut; HHN 2020).

3.2 Eurovignette Directive

The EU Directive 1999/62/EC[20] (with the amendment 2022/362/EU[21] and 2011/76/EU[22]) regulates the framework conditions for the use of certain transport routes by heavy goods vehicles. The regulation must be implemented by the member states if they levy charges on trans-European transport routes at national level.

Up to now, the truck toll in Germany has been made up of shares of the costs for infrastructure as well as external costs for air pollution and, since 2019, also noise pollution. The infrastructure costs are determined by the permissible gross weight and the axle configuration, the spread of which starts at 7.5 metric tons for commercial vehicles. The air pollution portion is classified according to Euro emission standards, while noise pollution costs are at a fixed amount. Toll rates are set based on a road cost report, which is prepared at five-year intervals. The maximum amounts for external costs are capped in the directive. The road cost report suggests that the actual costs of air and noise pollution are higher than the capped rates (Alfen Consult; AVISO; IVM; BUNG 2021).

In February 2022, the EU adopted a new revision of the directive, which provides for an extension to smaller truck classes and a classification of tolls according to CO_2 emissions. All member states that already levy tolls on heavy goods vehicles will have to extend the scope to heavy goods vehicles weighing 3.5 tons or more by March 2027. Differentiation according to CO_2 emission classes must take place by March 2024. However, the member states have leeway in terms of implementation. At least one of the following two options must be introduced:

- **Spreading of infrastructure charges:** Zero-emission vehicles can be exempted from tolls until the end of 2025, after which a reduction of between 50% and 75%, based on the worst CO_2 emission class, is possible.

- **Additional CO_2 component:** To account for the societal costs arising from CO_2 emissions from truck transport, a surcharge for CO_2 emissions can be added to the external costs. The EU proposes a CO_2 component of €100/t CO_2. Member states can increase this amount to €200 /t CO_2.

The basis for the CO_2 emission classes are the emission values recorded within the framework of the CO_2 emission standards (EU 2019/1242). For each new vehicle group regulated therein, a CO_2 -differentiated toll must be levied within 2 years. For example, for commercial vehicles between 5 to 16 tons, reference values for CO_2 emissions are not expected to be available until 2025.

Another objective of the amended Eurovignette Directive is to transfer time-based vignettes to distance-based charging systems. Distance-based tolls are already levied in Germany. The member states in which time-based tolls are levied have a deadline of 8 years for the changeover, with some exemptions.

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[20] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593444907573&uri=CONSIL:ST_13535_2018_INIT

[21] Directive (EU) 2022/362 of the European Parliament and of the Council of February 24, 2022 https://eur-lex.europa.eu/eli/dir/2022/362/oj

[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593444825883&uri=CELEX:32011L0076

In June 2023, the federal government introduced a legislative proposal to amend the Federal Highway Toll Act (BReg 2023): An additional CO_2 component of €200/t CO_2 is to be introduced in December 2023. For zero-emission trucks, an exemption from the toll is envisaged until the end of 2025, followed by a 75% reduction on infrastructure costs. In addition, the truck toll is to be extended to all heavy-duty vehicles with a gross vehicle weight of 3.5 tons or more in 2024. Exceptions are to apply to vehicles of craft businesses with a permissible gross weight of less than 7.5 tons. Another new feature is that half of the toll revenue may be used for purposes other than improving federal trunk roads, namely primarily for improving federal railroads. However, it remains unclear whether and to what extent the CO_2 price paid via the fuel price under the German Fuel Emissions Trading Act (BEHG) is to be offset against the CO_2 -based truck toll. The same applies to the CO_2 -pricing from the designated emissions trading in the transport and building sectors under the ETS 2, which is to be introduced from 2027 (cf. Section 3.4).

3.3 Alternative Fuels Infrastructure Regulation (AFIR)[23]

As part of the EU's *Fit for 55* package, the EU Commission has proposed a regulation on the development of alternative fuels infrastructures[24] in 2021, which is to replace the previous Directive 2014/94/EU. The proposed regulation sets binding national targets for the first time for the public-access[25] infrastructure of alternative fuels and charging power to ensure trans-European transport of alternatively powered vehicles. Member states are responsible for implementing and meeting the targets. The EU adopted the regulation on July 25, 2023. (AFIR 2023).

AFIR's focus is on expanding electric charging stations for passenger cars and commercial vehicles and, to a lesser extent, hydrogen refueling stations. The positive market developments of electric vehicles as well as the publicly stated strategies of manufacturers motivate the promotion of electrification of road transport including heavy-duty vehicles. The focus of the previous directive on LNG refueling stations[26] is weakened by the absence of concrete target formulations ("appropriate number"). A further innovation or specification compared to the current directive is the naming and differentiation of vehicle types. This takes into account the different requirements of passenger cars / light-duty vehicles and heavy-duty commercial vehicles in terms of space and power requirements at charging stations or refueling infrastructures.

The national minimum targets for public charging locations are based on distance-based and, for light motor vehicles (passenger cars and light commercial vehicles), additionally on fleet-based targets for infrastructure development to ensure sufficient area coverage and installed charging capacity. For heavy-duty vehicles, the AFIR envisions the infrastructure build-out requirements shown in Table 3-1. These should be interpreted as minimum requirements. For passenger cars, projections show that the requirements for public charging infrastructure in Germany significantly exceed the AFIR targets against the backdrop of the national fleet electrification targets (Oeko-Institut; EWI; FCN 2022).

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[23] AFIR: Alternative Fuels Infrastructure Regulation

[24] COM(2021) 559 final: Proposal for a regulation on the deployment of alternative fuels infrastructure, Brussels, 14.07.2021

[25] "Public-accessible" for the purposes of the ordinance means accessible to the general public regardless of whether the infrastructure is located on public or private property or access is limited (e.g., customer parking lots)

[26] LNG: Liquefied Natural Gas

Table 3-1: Extract of AFIR targets for heavy-duty vehicles (July 2023).

	2025	2027	2030	
Public charging infrastructure	**Minimum power per charging location**			**Specifications**
TEN-T overall network: one charging location at max. 100 km distance per direction of travel. (max. 120 km by 2025 on 15 %, by 2027 on 50 % of the network)	1,400 kW	1,400 kW	1,500 kW	Of which at least one charging point with 350 kW
TEN-T[27] Core network: one charging location at a maximum distance of 60 km per direction of travel. (max. 120 km by 2027)		2,800 kW	3,600 kW	Of which at least two charging points with 350 kW
Safe and secure parking areas[28]		200 kW	400 kW	At least 100 kW per charging point
Urban nodes	900 kW	1,800 kW	1,800 kW	At least 150 kW per charging point
Hydrogen refueling stations	**Minimum capacity per service station**			**Specifications**
TEN-T core network: One H_2 filling station at a maximum distance of 200 km per direction of travel.			1 t /day	Of which at least one tap with 700 bar
Urban hubs and, where appropriate, multimodal hubs.			1 refuel. station	

Source: AFIR 2023

The regulation also aims to harmonize national infrastructures and make them user-friendly by formulating requirements for technical specifications, the collection and provision of usage data, and transparent and non-discriminatory payment modalities. In addition, there are requirements for national policies to promote the expansion of alternative energy infrastructure in areas without fixed national targets (e.g. in the area of private infrastructure). The next revision of the regulation is set for 2026.

Electric Road Systems (e.g., overhead catenary systems) for heavy-duty vehicles are mentioned as newer technologies in the AFIR, for which technical standards are to be created and European member states are to submit regular progress reports with specific targets starting in 2027.

3.4 National climate protection targets and measures

The National Climate Protection Act sets out binding targets for reducing greenhouse gas emissions in Germany: By 2030, 65% fewer CO_2 equivalents are to be emitted than in 1990, and by 2045, Germany is to be climate neutral (KSG 2021). The contribution of the individual sectors is defined in a revised version of March 2023 via annual emission volumes set for the years 2020 to 2030 (KSG 2023). The transport sector has a reduction target to 85 million tons of CO_2 equivalents by 2030,

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[27] Trans-European Network Transport (EU Regulation 1315/2013)

[28] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13257-Road-transport-EU-standards-for-safe-and-secure-parking-areas-for-trucks_de

which is a 48% reduction compared to 1990 levels and also roughly halves GHG emissions from current levels. According to the 2021 projection report, there is a gap of 42 million tons of GHG emissions in 2030 compared to the emission levels prescribed in the Climate Protection Act (Oeko-Institut; Fraunhofer ISI; IREES; Thünen-Institut 2021). In its 2022 report, the Expert Council on Climate Issues points out that the measures announced by the German government to date are not sufficient to achieve the climate protection targets in the transport sector (ERK 2022).

For the first time, the German government has set a concrete savings target for road freight transport in its 2030 climate protection program: By 2030, one-third of mileage is to be covered by electric drives or electricity-based fuels (BMU 2019). The following key instruments for climate protection in road freight transport are already in force:

- **Purchase premiums:** With the funding guideline for *climate-friendly commercial vehicles and infrastructure*[29] , the German government has increased funding for the purchase of climate-friendly commercial vehicles. The subsidy covers 80% of the additional costs compared with a comparable conventional vehicle (previously 40%). The subsidy covers the following drive systems: battery-electric, fuel cell-electric, plug-in electric and overhead electric (incl. hybrid). The subsidy also includes the purchase of the refueling or charging infrastructure needed for operation. The decisive factor for approval is the amount of CO_2 saved per subsidy euro. Priority is therefore given to vehicles with low additional costs and high annual mileage. In the first two funding calls in 2021 and 2022, around 60% of the climate-friendly commercial vehicles applied for received funding[30] . Further funding calls are to follow. Funding of €1.6 billion has been approved for commercial vehicle procurement for the period from 2021 to 2024.

- **CO_2 price on fuels:** In 2021, a CO_2 price on fossil heating and motor fuels was introduced as part of the Fuel Emissions Trading Act[31] . This was to rise from an initial €25/t CO_2 to €55/t CO_2 in 2025 and then increase via certificate trading pricing. As a result of the sharp rise in energy prices in 2022, the increase was suspended as of 2023. It is not until 2024 that the CO_2 price is to rise to €35/t CO_2 and in 2025 to €45/t CO_2[32] . The CO_2 price of 30 €/t CO_2 in effect since 2022 roughly corresponds to costs of 2.4 ct/km for a tractor-trailer. At EU level, an emissions trading scheme for the transport and buildings sectors - known as ETS 2 - is to be introduced from 2027, which will form an increasing CO_2 price via a successive shortage of certificates, following the model of the existing emissions trading scheme for the energy sector and energy-intensive industry. The consequences for national emissions trading under the BEHG are as yet unclear.

- **Toll exemption:** Electrically driven commercial vehicles are still exempt from tolls until the end of 2023. In 2024, a CO_2 -differentiated truck toll is to be introduced, which will include reductions for electric drives (cf. Section 3.2).

- **Vehicle tax exemption:** Under the Motor Vehicle Tax Act (KraftStG), electric vehicles are exempt for a limited period of up to 10 years from initial registration. The exemption applies to first-time registrations of electric vehicles until the end of 2025 and is granted until the end of 2030 at the longest. However, for a tractor unit in emission class Euro VI, the vehicle tax of €665 per year represents only a small part of the operating costs.

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[29] https://www.balm.bund.de/DE/Foerderprogramme/KlimaschutzundMobilitaet/KSNI/KSNI.html

[30] Personal communication BAG

[31] https://www.bmuv.de/gesetz/brennstoffemissionshandelsgesetz

[32] Amendment to the Fuel Emissions Trading Act (SESTA) of 28.10.2022

The German government addresses the development of charging infrastructure in the *Master Plan Charging Infrastructure* II (BMDV 2022). This plan calls for a first tender for an initial charging network for heavy commercial vehicles in the third quarter of 2023. Together with the National Centre for Charging Infrastructure, the BMDV has set itself the task of analyzing demand and planning the expansion of the charging infrastructure for trucks by the end of 2022. The results are to be made available to investors and network operators. In addition, guidelines and sample layouts for the construction of public and company charging stations are to be developed.

4 Methodological approach and assumptions

This chapter provides an overview of the methodology of the analyses carried out and the data basis used. The market ramp-up modeling already used in previous work has been substantially further developed in the StratES project. One focus and declared objective is the more detailed representation of electric heavy-duty vehicles in the model used. In particular, the limited range of battery electric vehicles (BEV) is taken into account via different battery sizes, the definition of range requirements and different expansion scenarios of the charging infrastructure. In addition, the techno-economic parameters of the vehicles and framework data, such as the freight traffic forecast and energy price scenarios, have been updated. Another focus takes into account the required development of alternative energy infrastructures. Thus, the costs of construction and operation are passed on to the users in the modeling via an infrastructure levy. In addition, the methodology of a demand assessment is explained, which, based on the market ramp-up modeling, is to provide forecasts for a broad-scale and well-performing charging or refueling infrastructure for electric commercial vehicle fleets.

4.1 Market ramp-up modeling in TEMPS

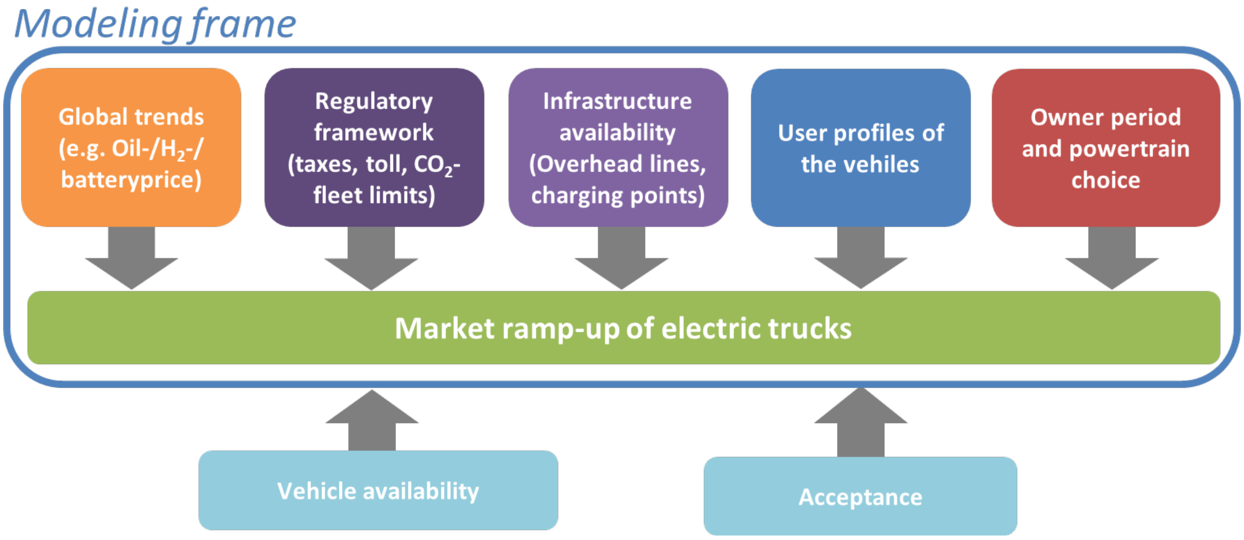
The TEMPS (**T**ransport **Em**issions and **P**olicy **S**cenarios) model developed at Oeko-Institut makes it possible to quantify the final energy demand and greenhouse gas emissions of transport for different scenarios and taking into account political and economic framework conditions. The model can be used to determine shifts in transport demand, the structure of new registrations and the number of vehicles, as well as energy requirements and greenhouse gas emissions.

The methodology of market ramp-up modeling with TEMPS is based on a bottom-up approach for the purchase decision and a subsequent calibration of the fleet to a given traffic performance (or stock). The starting point of the bottom-up modeling are user profiles that represent the driving behavior of the population or logistics companies in freight transport. A TCO calculation (Total Cost of Ownership) is used to determine the most favorable drive system and efficiency of the vehicle for each user profile. The sum of all selected vehicles is then weighted to determine the structure of new registrations in a given year. The vehicle fleet is then calculated on an annual basis using the traffic performance and survival curves of the vehicles. In the process, shifts in traffic between modes of transport (for example, from road to rail) are taken into account by means of price elasticities.

A schematic overview of the input variables is shown in Figure 4-1. The *availability of infrastructure (*overhead lines, charging and refueling infrastructure) and the *availability of vehicles* are essential prerequisites for a successful market ramp-up of zero-emission trucks. At the same time, the use of vehicles must be attractive for users. The cost-effectiveness of vehicle operation is central to this. The *regulatory framework conditions* (such as taxes, truck tolls, purchase premiums) have a major influence on the economic efficiency of vehicles. These can be influenced at national or European level and therefore offer opportunities for control. However, global trends (which are difficult to influence) can also be relevant for profitability - for example, the development of crude oil prices or battery prices. Whether vehicle deployment is actually attractive is also influenced by preferences in the logistics market and vehicle user profiles. For example, battery-electric trucks with a certain range cannot drive all user profiles as long as the appropriate charging infrastructure is not available along the highways. Even all-electric overhead catenary trucks are limited by their battery capacity to a certain range around the overhead line network (cf. Sect. 4.5.3).

For the modeling, it was assumed as a basic prerequisite that neither the availability of the vehicles nor the acceptance by the public or the buyers represent a restriction, since these two influencing variables are difficult to operationalize in the model. For example, there are neither provable data nor binding targets for the supply of vehicles on which a modeled supply market can be based. To approximate acceptance, the idea of payback periods is adopted from the predecessor project StratON (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020). The variation of payback periods or owner periods is more closely aligned with empirical data in the current project. All other aspects presented above are considered in the modeling. In addition, the principle of purely economic vehicle selection is extended for the modeling in StratES. If the total utilization costs for different drives are very close to each other, a stochastic random function decides on the drive choice (normal distribution with sigma = 0.015). The aim is to avoid a situation in which the economic potential of a drive system is very low, but still has too great a weight in the structure of new registrations.

Figure 4-1: Schematic representation of the market ramp-up modeling in TEMPS.



Source: Own representation

4.2 Freight transport demand

Freight transport demand is input variable for the market ramp-up modeling and is taken from the transport demand model TREMOD[33] for the years 2010 till 2021. For the transport demand forecast, historical data are used with a growth rate from the reference scenario of the Mobility and Fuel Strategy (MKS) REF-2017 (Schade et al. 2018). The trend update of freight transport volumes is strongly based on the development of gross domestic product (GDP) and the related trade flows and transports. The assumption of steady GDP growth therefore means that freight transport performance also increases proportionately. While 440 billion ton kilometers were transported by road in 2010, transport performance will grow by 45% to around 656 billion ton kilometers by 2045.

The assumed development of freight transport performance by mode of transport is displayed in Figure 4-3. In the forecast, rail freight's share of transport performance, currently around 19 %, falls to 17 % in 2045. This means that the forecast fails to achieve the German government's target of increasing the share of rail transport in transport volume to 25 % by 2030. (SPD; Alliance 90/The

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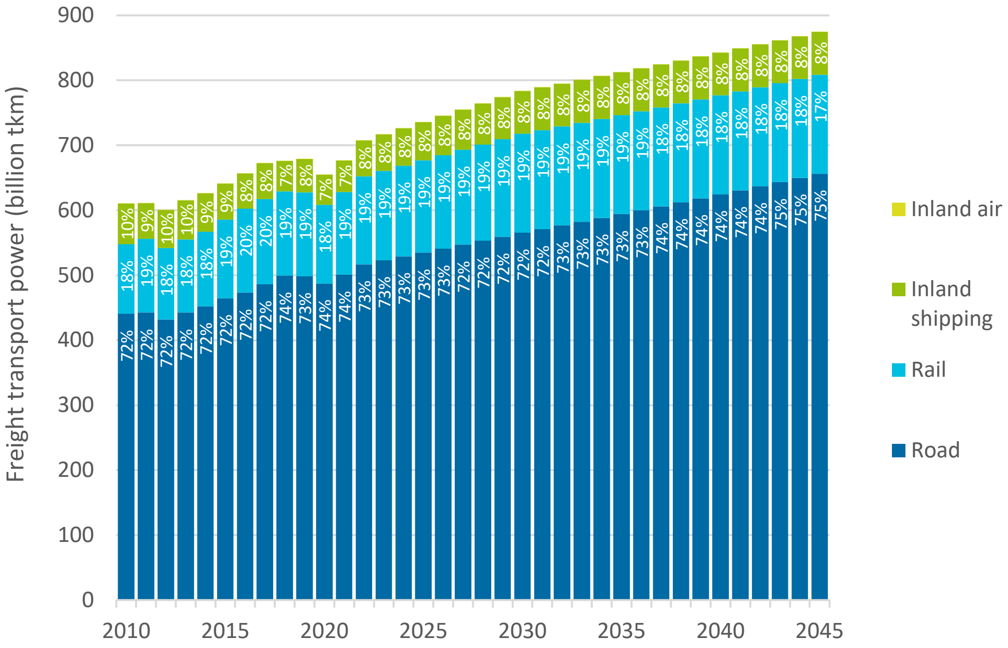
[33] https://www.ifeu.de/en/methods-tools/models/tremod/

Greens; FDP 2021). The reason for this is the sharp rise in freight transport, which, according to the basic data used, is mainly covered by road transport. Within the TEMPS model, shifts to rail, ship or air are represented by price elasticities. However, the shift potentials are not sufficient to cushion the increase in transport volume on the roads.

Figure 4-2 **Assumed development of freight transport performance by mode of transport based on the MKS reference scenario REF-2017.**



Source: Own representation based on TREMOD and Schade et al. 2018

4.3 Vehicle configuration and costs

In TEMPS, four size classes are distinguished for heavy-duty vehicles (cf. Table 4-1). Up to now, all of these size classes have been almost exclusively vehicles with internal combustion engines (ICEV: internal combustion engine vehicle) for diesel fuels. For the alternative drive and fuel concepts, a trend toward electric drives is becoming increasingly apparent. In this study, battery electric vehicles (BEV: battery electric vehicle), fuel cell electric vehicles (FCEV: fuel cell electric vehicle) and battery electric vehicles with pantographs for dynamic charging on overhead catenary systems (O-BEV: overhead catenary battery electric vehicle) are investigated in different combinations. While BEV and FCEV can be used for all size classes, overhead catenary technology is only available in the model for tractor-trailers.

For each size class and drive option, a fictitious vehicle is configured to represent the average of vehicles in the respective segment. An overview of relevant parameters, such as the energy consumption of the new vehicle, the vehicle range and the purchase price, is provided in the following table Table 4-1. Different ranges are taken into account for BEVs and O-BEVs, which are indicated by the numerical value after the drive abbreviation. For example, a "BEV400" has a range of 400 km, with a residual charge of 15% considered as a buffer in the design of the battery storage. For FCEVs, the range varies with the size class between 450 km for trucks up to 12 tons gross vehicle weight and 1000 km for tractor-trailers.

Table 4-1: Characteristic values and costs of the modeled heavy-duty vehicles in the year 2030.

Size classes by gross vehicle weight		**Truck from 3.5 to 7.49 t**	**Truck from 7.5 to 11.99 t**	**Truck from 12 t**	**Tractor-trailer**
Engine power	kW	120	170	325	350
Battery capacity per range[1]					
BEV200	kWh	90	130	250	320
BEV400	kWh	185	270	510	665
BEV600	kWh	290	400	770	1.025
O-BEV100	kWh	-	-	-	170
O-BEV200	kWh	-	-	-	340
Hydrogen storage (gaseous at 700 bar)					
FCEV	kg H_2	-	15	41	72
- Range	km		450	700	1,000
Energy consumption[2]					
ICEV	kWh/km	1.14	1.79	2.48	2.81
BEV200	kWh/km	0.38	0.56	1.05	1.37
BEV400	kWh/km	0.39	0.57	1.08	1.41
BEV600	kWh/km	0.41	0.57	1.09	1.45
O-BEV100	kWh/km	-	-	-	1.44
O-BEV200	kWh/km	-	-	-	1.43
FCEV	kWh/km (kg$_{H2}$ /100km)	-	1.13 (3.4)	1.92 (5.8)	2.41 (7.2)
Purchase price[3]					
ICEV	€$_{2020}$	40,500	66,900	83,200	152,100
BEV200	€$_{2020}$	42,350	72,800	90,700	158,700
BEV400	€$_{2020}$	55,000	93,600	119,250	201,600
BEV600	€$_{2020}$	67,650	114,700	147,850	244,550
O-BEV100	€$_{2020}$	-	-	-	166,800
O-BEV200	€$_{2020}$	-	-	-	188,250
FCEV	€$_{2020}$	-	106,150	165,900	254,250

[1] In the dimensioning of the battery capacity per range, a residual battery charge of 15% is taken into account as a buffer.

[2] The indicated energy consumption corresponds to the fleet average for the respective size class.

[3] The purchase prices are given as examples for the most common user profile. Depending on the user profile, the purchase price and energy efficiency of the vehicle may vary along the cost curves. The price given for tractor trailer includes the purchase of a semitrailer.

Source: Own calculations

The maximum range configured for BEVs is 600 km. There are two reasons for this restriction: First, estimates of powertrain weight savings, taking into account a legally permissible additional weight of 2 metric tons for zero-emission vehicles, show that about 3-4 tons of battery weight can be installed in tractor-trailers without significantly limiting the available payload (Oeko-Institut; HHN 2020, ICCT

2021b). Assuming a specific energy of the battery system in 2030 of 250 kWh/t, ranges higher than 600 km without corresponding payload losses are likely to be possible only with drastic advances in battery development. On the other hand, the legally prescribed steering breaks after 4.5 hours of driving at a maximum speed of 80 km/h allow distances of around 360 km to be driven in one piece. If the driving breaks can be used to recharge the battery, ranges of 400 km are sufficient in theory. The economic interaction between a vehicle with smaller battery storage (cheaper to purchase) and a higher demand for public high-power charging electricity (likely to be more expensive) is investigated in this study.

The dataset of vehicle costs and energy consumption was updated and fundamentally expanded as part of this study. The historical energy consumption of the modeled vehicles continues to be based on TREMOD. Cost curves were introduced for the projections, which establish a functional relationship between the increase in efficiency and the additional costs of a vehicle compared to a reference vehicle. The cost curve methodology is consistent with the approach described by the Joint Research Center in 2018 (EC 2018). The reference is a conventional diesel vehicle of the same size class from 2020. In the modeling, buyers opt for the most favorable combination of vehicle efficiency and additional price in their application profile. As a rule, the additional costs increase with the energy efficiency of the vehicle. On the other hand, the cost-intensive battery storage for BEVs - with a constant range - can be dimensioned smaller for more efficient vehicles, which means that efficiency gains in the trend can deliver advantages in terms of energy costs and purchase prices.

The purchase prices vary according to the user profile and design point on the cost curves. Table 4-1 shows examples of purchase prices in the most common user profiles of the size classes for the modeled drive options. The energy consumption listed represents the average value of the modeled new vehicle fleet in 2030. Further efficiency increases in the subsequent years up to 2045 occur only to a small extent for all drive systems considered (up to 4% compared to 2030). For the purchase prices, there are in some cases considerable cost reductions up to the year 2045. These are discussed in connection with the results of the total cost of ownership calculations in Sections 5.1.2, 5.2.2 and 5.3.2 are quantified. In addition, the total costs include a residual value of between 15 % and 24 % of the purchase price for all drives and size classes.

Insurance, maintenance, repair and other accommodation costs are included as operating costs. The sources used are those published in the industry magazine *Lastauto* Omnibus (Rosenberger et al. 2018) reported values for conventional vehicle models. For the electric drives, the hull portion of the insurance costs (own damage) is scaled as a function of the purchase price. Maintenance and repair costs were reduced in consultation with industry experts for the electric drives because, for example, costs for urea solutions for exhaust aftertreatment are eliminated and costs for lubricants and wear parts can likely be reduced. Other accommodation costs, such as fleet management or depot space, are set at the same level for all drives.

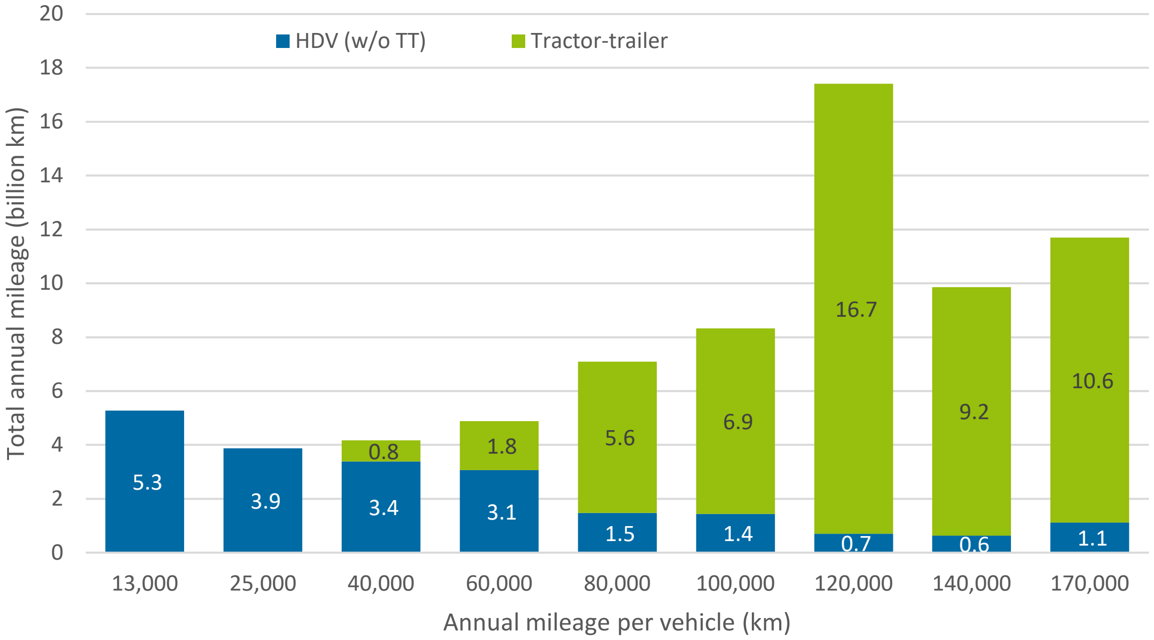
4.4 User profiles

The user profiles form the cornerstone for market ramp-up modeling. They are intended to exemplify the user behavior in heavy goods traffic as well as the special logistical and technical requirements. All user profiles are weighted so that they represent the national freight traffic volume in its entirety. The user profiles are derived on the basis of the empirical mileage surveys *KiD2010: Motor Vehicle Traffic in* Germany (BMVI 2010) and *FLE2014: Driving Performance Survey* (BASt 2015). The profiles are defined by four characteristics, each of which is differentiated into classes: Vehicle size, annual mileage, owner period and range. For overhead catenary trucks, the share of electric driving on the overhead network is an additional parameter. In total, we model 1552 truck user profiles. A frequency distribution is stored for all characteristics, which together result in a weighting of the profiles. The classification of vehicle size has already been introduced in the previous section, in the following the three further characteristics are described in more detail.

4.4.1 Annual mileage

The annual mileage derived from the FLE2014 is divided into annual mileage classes for each size class, that are then assigned with weighting factors. Figure 4-3 shows the distribution of annual mileage differentiated by size class, with the three truck size classes shown aggregated. From annual mileages of 80,000 km per year, tractor-trailers have a very high share of the annual mileage, while lower annual mileages are mainly covered by the other truck size classes. Tractor-trailers thus bear the main burden of mileage and, as a consequence, of GHG emissions in road freight transport.

Figure 4-3: Weighting of annual mileage classes for heavy-duty vehicles



The horizontal axis indicates the respective upper limit of the annual mileage class, e.g. 40,000 km means vehicles with annual mileages of 25,000 to 40,000 km.

Source: Own calculations based on FLE2014

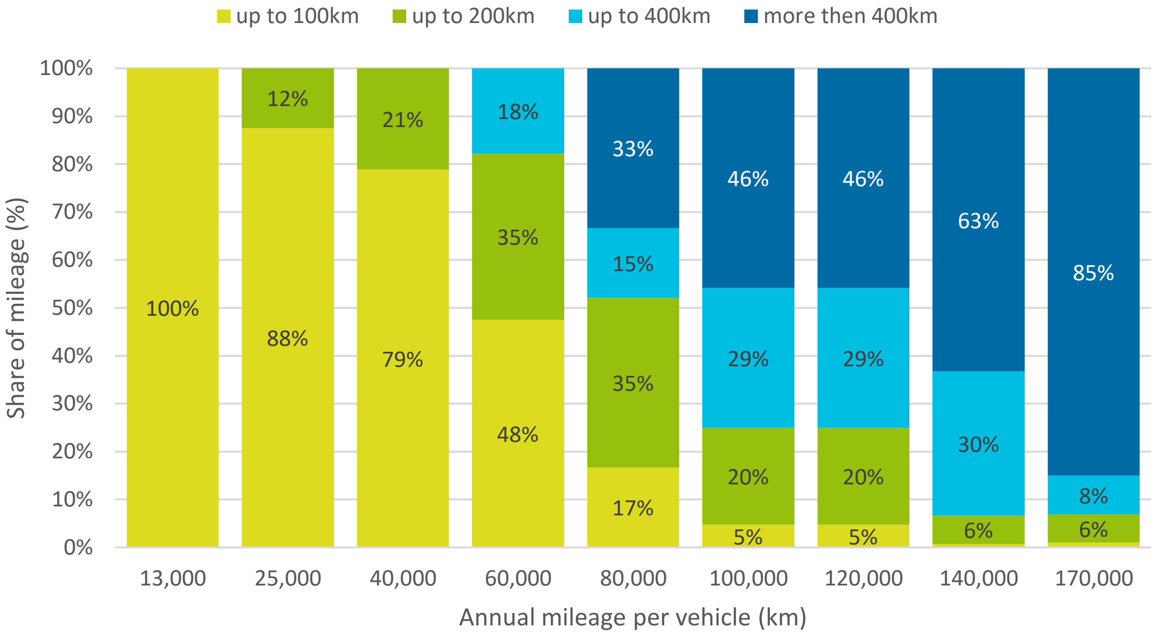
4.4.2 Range requirements

The range requirements of the routes are of great importance for the possible applications of electric drives. BEVs in particular will probably carry less storage capacity in the vehicle in some cases, even in the future, than is required for day trips in long-distance traffic. In order to get closer to the requirements for recharging options and to be able to better map the possible uses of BEVs depending on the battery storage, the range requirements of the vehicle use and the available charging options, range classes are implemented in the user profiles.

In addition to the total daily mileage, the maximum length of a single trip is taken into account for the vehicle use of BEVs. To derive the range classes, the information on the number and length of single trips in KiD2010 was linked to the annual mileage in FLE2014. As Figure 4-4 shows, four range classes were distinguished: single trips up to 100 km, from 101 to 200 km, from 201 to 400 km, and over 400 km. The last category, from 400 km, is given by the fact that truck drivers have to take a legally required break from driving after 4.5 hours of driving and can therefore drive a maximum of around 400 km at a time.

The data obtained show a clear correlation between the annual mileage and the range class: while moderate annual mileages of up to 40,000 km per year in the sample of mileage surveys are exclusively made up of single trips of up to 200 km in length, from 100,000 km annual mileage onward about half and from 140,000 km per year onward well over half of the single trips have lengths of over 400 km. A BEV with a range of 400 km would therefore not be able to make a single trip for the most part without stopping to recharge.

Figure 4-4: Weighting of the range classes within the annual mileage classes (maximum length of a single trip).



Source: Own calculations based on FLE2014 and KiD2010.

4.4.3 Imputed useful life (owner period)

The imputed useful life indicates the period of time planned for the use of a newly acquired vehicle for refinancing. The actual owner period may differ from the imputed useful life. In the modeling (and in the following), the terms are used synonymously. For logistics companies, the owner period represents an important criterion for the amortization of the purchase price and thus the purchase decision. The total cost of ownership is summed up over the owner period, so that a higher purchase price can be offset by more favorable operating costs over the holding period. As in the previous StratON project, five owner periods are distinguished for each vehicle size category in order to reflect different amortization periods for the purchase - and thus, among other things, the different risk aversion of vehicle owners. For short owner periods, there is less time to compensate for the higher purchase prices of electric commercial vehicles through lower operating costs.

The owner periods used in the current project are based on a standardized online survey of transport companies in spring 2021 (Oeko-Institut; Hochschule Heilbronn 2022). With the owner period shown in Table 4-2 the results of the survey were approximated using a step function and implemented in the modeling.

Table 4-2: Variation of owner period classes for spreading user profiles

Owner period per size class	3 years	4 years	5 years	6 years	7 years	8 years	9 years
Truck from 3.5 to 7.49 t			15%	20%	30%	20%	15%
Truck from 7.5 to 11.99 t			15%	20%	30%	20%	15%
Truck from 12 t		15%	20%	30%	20%	15%	
Trucks and semitrailers	15%	20%	30%	20%	15%		

Source: Own assumptions based on Oeko-Institut; Hochschule Heilbronn 2022

4.5 Availability of energy infrastructures

A significant extension of the modeling in this project context is the consideration of charging options and derived restrictions for the use of BEVs. The development of a public charging network for heavy-duty vehicles is still in its infancy. Based on the range requirements in the user profiles described in the previous sections (Sect. 4.4.2) and the ranges available per vehicle configuration (Sect. 4.3), BEVs face restrictions on vehicle deployment, i.e., BEVs are not allowed as a propulsion option in the model in user profiles with additional range requirements. The increasing availability of comprehensive and powerful charging options will gradually reduce the range restrictions and enable the universal use of BEVs. The model-based approach is described in detail in the following sections.

No model-side restrictions on vehicle operation are assumed for FCEVs. It is anticipated that FCEVs will achieve a range of up to 1,000 km for long-distance traffic toward the end of the decade. Accordingly, almost all daily trips can be covered without a stopover for refueling. The dependence on a locally and temporally available energy supply is therefore lower than for BEVs. Although a small area coverage of hydrogen refueling stations[34] would mean that some considerable detours for refueling would have to be accepted, we nevertheless assume that FCEVs can be used in all user profiles without any deployment restrictions.

For O-BEV, the core network of overhead catenary systems developed in the StratON project will be adopted. (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020). Beyond the highways electrified via overhead lines, the application possibilities of O-BEVs depend, analogously to BEVs, on the battery-related range of the vehicles. The expansion scenarios for the overhead line network and the resulting deployment restrictions are explained in more detail in the following sections.

4.5.1 Charging scenarios and deployment restrictions for BEVs

With a technically limited vehicle range and range requirements defined in the user profiles, the possible uses of BEVs are essentially determined by the availability of recharging options. In order to draw as realistic a picture as possible of the expansion of the charging infrastructure and to derive

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[34] The AFIR demands a maximum distance of 200 km between two hydrogen refueling stations, while a maximum distance of only 60 km is required for charging hubs along main transport routes (cf. Sect. 2.2).

a link between infrastructure expansion and drivable profiles, three infrastructure expansion stages were defined, which are shown schematically in Figure 4-5.

- **"Daily"** describes a configuration stage in which the battery storage can only be fully charged once per operating day (usually overnight). The range requirement for vehicle use is therefore determined exclusively by the daily mileage. This expansion stage corresponds to the status quo, i.e. BEVs have so far been used in combination with depot charging points on tours that can be represented with available vehicle ranges without intermediate charging.
- **"Everystop"** describes an expansion stage in which, in addition to one-time full charging of the battery system, recharging between two transport trips is also possible. However, interruptions of a trip are not permitted. The range requirement is determined accordingly by the longest single trip to be covered. In this expansion stage, the range of uses for BEVs is extended, for example, by allowing loading and unloading times to be used for recharging or, more generally, by allowing public or private charging facilities to be used at the destination. As BEVs begin to ramp up, this variant is expected to replace the *daily* expansion stage in the coming years.
- **"Highway"** describes the target state in which intermediate charging is possible at any time in addition to the charging options described above. For this purpose, a broad-scale and well-performing charging network is available, which allows the battery to be recharged during the legally prescribed driving breaks. Range requirements thus become obsolete and BEVs can theoretically be used in all user profiles. The megawatt charging standard required in this expansion stage is still before market launch. In addition, the required planning and approval processes result in uncertainties about the realization times of this expansion stage.

In the three expansion stages, therefore, essentially the same process described in Sect. 4.4.2 is varied in the usage profiles. BEVs are only permitted in user profiles in which the range requirement can be met. For example, in the *daily* variant, a BEV400 can only drive user profiles with daily mileages up to 400 km, while in the *everystop* expansion stage, higher daily mileages are possible, provided the individual trips are shorter than 400 km. In the target state *highway,* all user profiles are enabled. The three expansion stages can be combined via weighting factors.

To investigate the effect of the availability of recharging options on the market ramp-up of BEVs, three charging scenarios are defined, consisting of a dynamic mix of the three expansion stages. Here, we assume that the share of *daily* is initially 100%. With megawatt charging availability beginning in 2024, the *highway* share increases to 100% by the time the charging network is fully deployed. The three charging scenarios we have developed for the modeling work differ in terms of when the charging network is fully developed: from 2030, from 2035 or from 2040.

This approach does not take into account that time may be lost due to charging stops, for example when charging stops do not coincide with driving breaks or longer waiting times at charging stations would be needed. Accordingly, we assume that charging stops can be integrated into existing operational patterns. Accordingly, no time losses are priced into the total cost calculations for BEVs. Also not considered are potential adaptations of established usage patterns to the shorter ranges of electric drives. The modeled user profiles are based on mileage surveys generated almost exclusively with conventional diesel vehicles. Since possible adjustments are difficult to estimate from today's perspective, the range restrictions in the modeling represent an attempt to account for the shorter ranges of BEVs in the market ramp-up and to quantify the effect of the expansion rate of charging infrastructure.

4.5.2 Use of different types of chargers

In the case of increasing electrification of road freight transport, public charging options will become more and more important. While the availability of charging infrastructure is described by the charging scenarios, the introduction of concrete charging options with different performance and different electricity prices should enable a more differentiated design of the infrastructure needs and thus the market ramp-up of battery-electric drives.

The definition of charging point types builds on use cases and definitions in previous studies (Oeko-Institut; EWI; FCN 2022, NOW 2022a, T&E, ACEA 2020, CE Delft 2019) and on existing and foreseeable charging standards. The most important differentiating characteristics of the charging point types are the charging power, the charging time, and the location in the private or public space. Four charger types are distinguished:

- **Depot Charging System (DCS)**: The foundation of the charging infrastructure is formed by operational charging solutions in depots. For modeling purposes, we assume that vehicles are fully charged with a charging capacity of 150 kW within 8 hours of idle time. The utilization of a depot charging point is 1.5 trucks per day (CE Delft 2019).

- **Night Charging System (NCS):** The public version of the depot charging point is NCS at rest stops, e.g. for tours lasting several days without private recharging facilities. Analogous to DCS, we assume a charging power of 150 kW and a charging time of 8 hours. The load factor is also 1.5 trucks per day.

- **Combined Charging System (CCS):** Charging points with this charging standard enable charging powers of 350 kW. Areas of application are conceivable both in public areas and in private constellations (customer charging). The charging times are shorter. In order to evaluate the potential for use within the driving break, we calculate charging times of 30 minutes. The local utilization of the charging points is determined from the maximum daily demand (cf. section 4.8).

- **Megawatt Charging System (MCS)**: The MCS standard allows charging capacities of over one megawatt. The application area is publicly accessible charging hubs along the highway network. For the modeling, we assume a charging nominal power of 1,000 kW and a charging time of 30 minutes. The local utilization of the charging points is determined from the maximum daily demand (cf. Sect. 4.8).

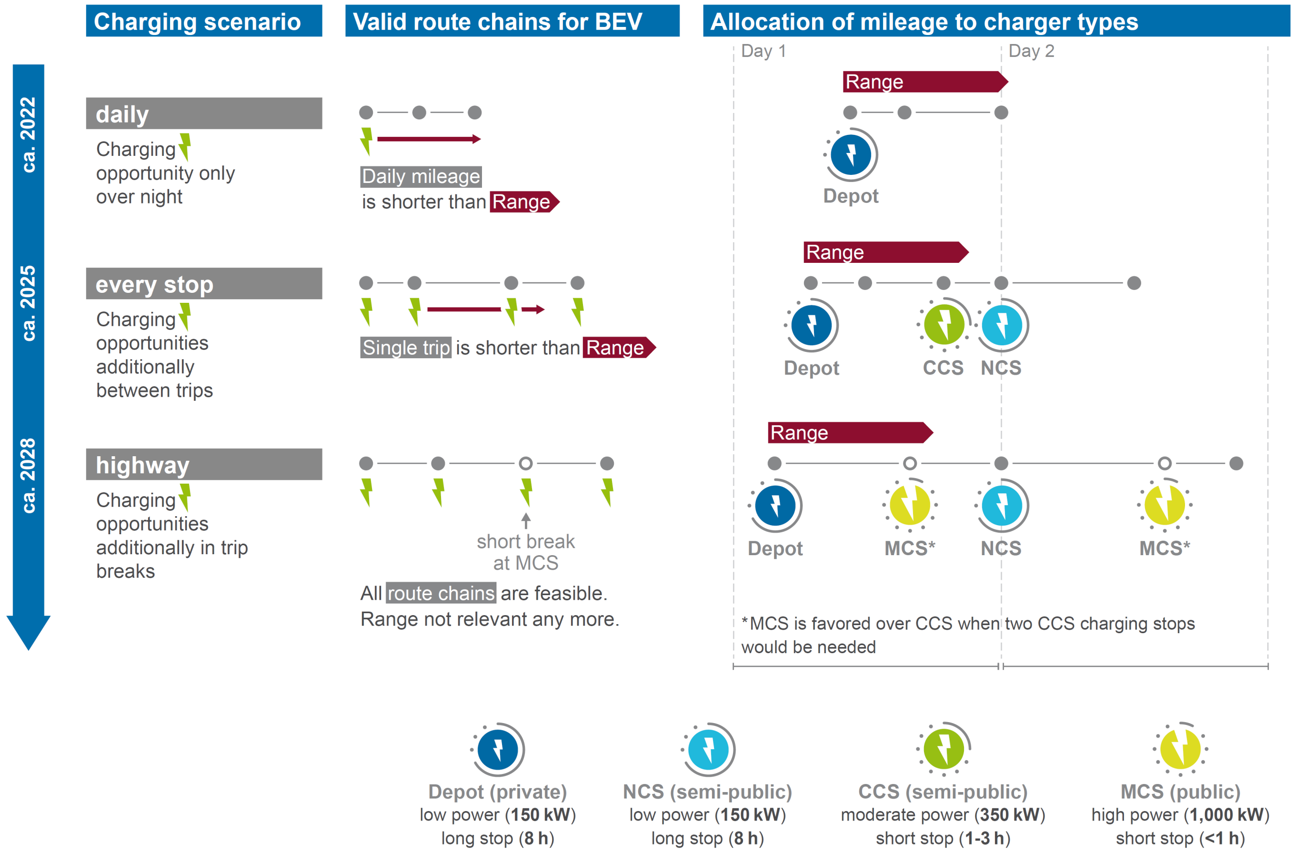
From today's perspective, the extent to which the charging types listed will be used in the future can only be estimated on the basis of assumptions. Analogous to the decision to purchase a new vehicle, we assume that the use of the charging infrastructure will be predominantly economically driven. In addition to economic efficiency, time considerations will probably be decisive. This leads to the following hypotheses as a basis for the methodological approach, which were discussed in detail with experts during the design phase:

- **Economic efficiency:** The choice of charging point type is primarily based on the charging price, which is expected to increase with the charging power provided. Accordingly, the most favorable option is to fully charge the battery storage once per operating day at DCS or NCS charging points. The moderate charging powers also have a positive effect on battery life, which provides another economic incentive. However, this effect was not quantified in the modeling.

- **Time efficiency:** In addition, for trips beyond the battery ranges, recharging stops at CCS or MCS charging points will be necessary. If a recharging stop at a CCS charging point is not sufficient to meet the daily mileage, an MCS charging point will be used instead. This is based on the assumption that higher charging prices for MCS charging are less significant than the time costs that would be incurred by an additional stop.

The usage logics based on these assumptions were applied to the trip chains available in KiD2010. A trip chain describes several consecutive transport trips and can be of one or several days' duration. The methodology of assigning load types to mileage is shown for exemplary trip chains in Figure 4-5 for exemplary trip chains. This also illustrates the relationship to the charging scenarios: while DCS and NCS are available in all three charging scenarios, CCS is only provided from the *everyday* charging scenario and MCS is only provided in the *highway* scenario (cf. Section 4.5.1).

Figure 4-5: Methodology for varying charging infrastructure availability, deployment restrictions of BEVs, and distribution of mileage across charger types.



Source: Own representation

The trip chain begins in each case with a full charge of the battery at the depot. Additional range requirements on the same day are assigned to either CCS or MCS charging points as described above. For trips lasting several days, the battery is fully charged overnight at NCS charging points for the following days of operation. The methodology presented was used to determine the distribution of total mileage among the different charging options per size class, battery range, and charging scenario.

This approach does not aim to fully represent the diversity and complexity of road freight transport. Rather, it serves to classify the demand estimate for the different charging point types based on it using a simple logic. For example, the demands for CCS and MCS charging points show the mileage share that cannot be covered by a single battery recharge. In practice, there may be some shifts between charging point types. For example, in multi-shift operation, long charging times in the depot are not feasible. This proportion will therefore have to be served by fast charging points (CCS and MCS) in addition to the designated demand. Conversely, today's usage patterns may change as a result of the changed boundary conditions of electric vehicles and the effect of charging electricity prices.

4.5.3 Overhead catenary network and deployment restrictions for O-BEVs

The modeled overhead contact line network is based on the preliminary work in the project StratON (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020). In this project, a core network of about 4,000 km in length (per direction of travel) was developed using a selection of high-traffic federal highways (BAB). Around 90% of this core highway network will be electrified by installing overhead contact line systems. In this study, different time stages of the core network are examined in scenarios. We distinguish between an installation of the approximately 3,800 km of overhead contact line by the year 2035 or a delayed construction until the year 2040.

For O-BEV, the range requirements refer to the up- and downstream routes away from the overhead network. A trip dataset is available from StratON based on traffic modeling for the forecast year 2050 by Intraplan Consult. Table 4-3 shows the annual average daily traffic volume (AADT) broken down by distance classes in the upstream and downstream routes (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020). All trips made by trucks with 4 axles or more (e.g. tractor-trailer) for at least 100 km on the overhead core network are taken into account. Highlighted in green are trips that are suitable for O-BEV use because the up- and downstream distances are each no longer than 250 km. If the mileage of these trips is related to the territorial (domestic) mileage for trucks with 4 axles or more (approx. 46 billion km/year), the technical deployment potential of the kilometers that can be driven by O-BEVs on the overhead contact line network is about 25 % of the total mileage. Added to this are the up- and downstream distances that can be covered by the battery storage charged on the overhead contact line or in the depot.

A higher potential is possible in the case of an international expansion of overhead contact line technology, since some trip shares up- and downstream of the network, especially in the high distance classes (251 - 500 km), occur abroad. Without the filtering of trips with longer up- and downstream distances than 250 km, the technical deployment potential increases to around 50 % of the territorial mileage.

In the user profiles, the range requirements of the up- and downstream lengths are taken into account. Analogous to BEVs, O-BEVs are only enabled in user profiles in which the range of the vehicle can serve the range requirement. For O-BEVs, it is taken into account that the battery can be recharged at the overhead line while driving. In addition, the battery can be recharged in depot so that the full battery capacity is available again for the next route.

Table 4-3: Journeys on the overhead catenary (OC) network from StratON broken down in upstream, main and downstream parts (for trucks with 4 axles or more with a travel distance of more than 100 km in the main run).

Upstream of OC-network		Main run on OC-network			Downstream of OC-network	
Distance class in km	**Truck-km [veh-km/d][1]**	**Number of trucks [veh/d]**	**Truck-km [veh-km/d]**	**Share of total truck km**	**Distance class in km**	**Truck-km [veh-km/d]**
up to 100	2,511,947	89,554	23,049,673	42.8 %	up to 100	2,468,570
up to 100	535,757	17,247	4,958,947	9.2 %	101 - 250	2,696,123
up to 100	223,179	6,762	2,198,149	4.1 %	251 - 500	2,298,770
up to 100	233,426	7,528	2,579,776	4.8 %	from 501	5,367,500
101 - 250	3,204,367	19,816	5,736,677	10.7 %	up to 100	612,843
101 - 250	994,133	5,903	1,990,150	3.7 %	101 - 250	951,683
101 - 250	656,770	3,709	1,316,571	2.4 %	251 - 500	1,251,157
101 - 250	577,530	3,351	1,260,085	2.3 %	from 501	2,457,063
251 - 500	2,966,820	8,850	2,699,306	5.0 %	up to 100	286,948
251 - 500	1,281,310	3,801	1,336,105	2.5 %	101 - 250	652,890
251 - 500	585,907	1,759	604,383	1.1 %	251 - 500	596,010
251 - 500	573,913	1,733	591,140	1.1 %	from 501	1,394,833
from 501	5,696,767	8,162	2,918,327	5.4 %	up to 100	277,192
from 501	2,633,257	3,676	1,483,214	2.8 %	101 - 250	638,360
from 501	1,479,230	1,971	669,305	1.2 %	251 - 500	647,517
from 501	827,190	1,126	408,093	0.8 %	from 501	793,930

[1] For extrapolation to the annual mileage, 300 operating days per year are calculated.

Source: Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020

4.6 Costs of energy infrastructures

The switch to electric vehicle drives requires the development of new energy supply infrastructures. For commercial vehicles, this development is still at the beginning (cf. section 2.2). Ideally, the new energy infrastructures will be financed by their use. The aim is therefore to calculate specific costs of the new energy infrastructures that can be passed on to the users as components of the operating costs (e.g. energy costs or tolls).

Table 4-4 summarizes the key parameters of the calculation: The absolute costs of charging points, hydrogen filling stations and overhead line systems are derived from the capital costs (capex), the operating costs (opex), the financing period and an average financing rate (WACC: Weighted Average Cost of Capital). The cost data are taken from literature sources and, together with the financing period and rate, were checked for plausibility in discussions with experts. Due to the lack of practical experience, there are nevertheless uncertainties regarding the investments, as the cost framework shown illustrates. For example, construction costs for the grid connection vary depending on local conditions. To ensure financing, we use the upper cost figures shown for the calculations.

We assume that charging points and hydrogen refueling stations are predominantly financed by the private sector, while the expansion of overhead lines on a German core network is a large-scale project organized and financed by the state, analogous to the expansion of the electricity grid. The financing period is assumed to be shorter for the private infrastructures (15 years) than for the overhead catenary systems, since the payback period and subsequent profit opportunities are likely to have a higher weight in the case of privately financed infrastructure.

The specific costs relate the annuity of the investment to the annual amount of energy provided at a charging point or a dispenser of a hydrogen refueling station. The projection is based on an estimate of the average daily utilization. For the overhead line network, the proportion of travel on the overhead line relative to total mileage is the basis for estimating utilization. The figures shown in Table 4-4 already assume an established use of the infrastructures of 8-12 hours per day.

Table 4-4: Assumptions on energy infrastructure costs

		DCS-CP	NCS-CP	CCS-CP	MCS-CP
Capex[1]	k€	45-110	45-110	125-215	400-800
Opex[1]	% cpx p.a.	2 %	2 %	2 %	2 %
Financing duration	Years	15	15	15	15
Interest rate / WACC	%	7 %	7 %	7 %	7 %
Rated power[2]	kW	150	150	350	1000
Charging time per truck	h	8	8	0,5	0,5
Trucks per day[3]	Vehicle/ day	1,5	1,5	16	16
Specific costs	ct/kWh	2.9	2.9	3.8	4.9
		H_2 ref. station (per dispenser)		**Overhead line system (per km)**	
Capex	k€	2,000-3,500		k€	2,400-3,200
Opex[1]	% cpx p.a.	5 %		% cpx p.a.	2 %
Financing duration	Years	15		Years	25
Interest rate / WACC	%	7 %		%	5 %
Rated power	kg/h	150		kW/km	1,400
Refueling time per truck	h	0,33			
Trucks per day	Vehicle/ day	24		% Mileage	25%
Specific costs	ct/kWh	4.5[4]		ct/kWh ct/km	3.1 5.3

[1] Hardware, planning, permitting and installation (excluding lease, battery storage and grid expansion costs).

[2] Ratio of average power to rated power: 0.85

[3] Assumes 300 operating days per year.

* Conversion to EUR/kg based on the lower heating value of hydrogen (120 MJ/kg): 3 ct/kWh = 1 EUR/kg

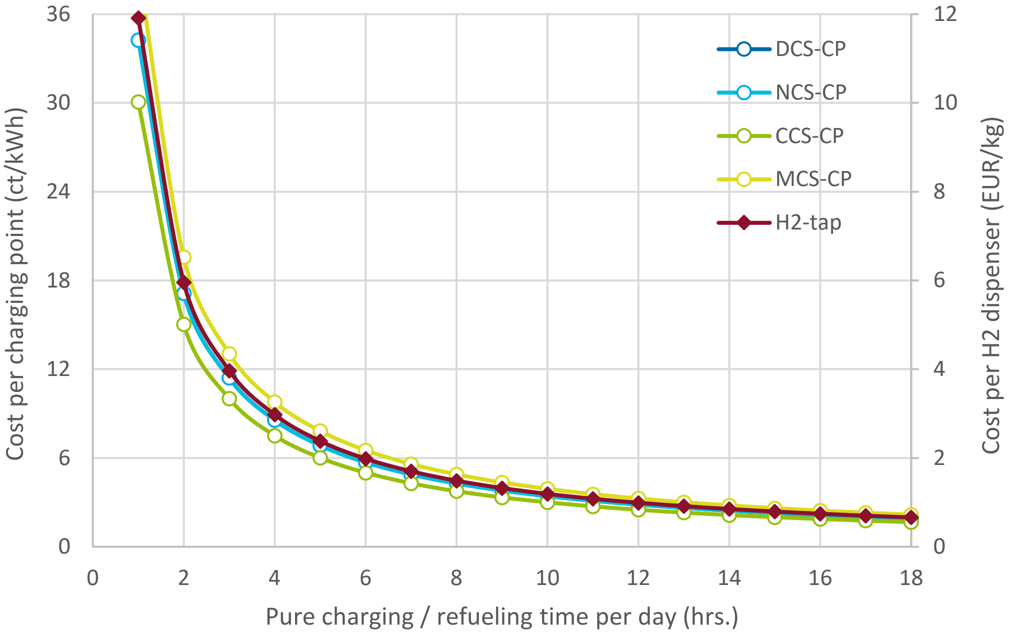
Source: Own calculations based on Oeko-Institut; EWI; FCN 2022, Fraunhofer ISI 2020b, ICCT 2022a and Oeko-Institut 2018

As a result, the specific costs range between 2.9 and 4.9 ct/kWh for charging points (depending on the charging point type), 4.5 ct/kWh for H_2 dispenser and 3.1 ct/kWh for overhead line systems. The costs for setting up the new energy infrastructures are therefore moderate after allocation to the units of use. Refinancing is possible via a surcharge, i.e., an infrastructure levy, in the energy price or as part of the toll charges. However, the infrastructure levy does not take into account costs for the expansion of electricity grids or the development of hydrogen transport infrastructures. More extensive analyses are lacking for these estimates.

Energy infrastructure utilization is expected to be lower in the early market phase and in lower-traffic locations than in Table 4-4 is indicated. The increase in specific costs of charging and hydrogen refueling infrastructure with decreasing utilization is shown in Figure 4-6. For example, at an average utilization of 2 hours per day, the specific costs of megawatt charging points increase to 20 ct/kWh. Per hydrogen dispenser, 6 EUR/kg would be incurred for the construction and operation of the refueling system alone. Similarly, an overhead line system operating at only 50% capacity would incur twice the specific costs listed in Table 4-4.

While high utilization of the energy infrastructures is likely via the necessary rapid ramp-up of electric commercial vehicles, the risk of low utilization in an initial market phase and in low-traffic areas is likely to be factored into pricing. As a result, moderate specific costs, particularly for privately financed energy infrastructures, could be significantly higher in practice, or expansion could be limited to lucrative locations. This study addresses the uncertainty about the level of infrastructure charges via two different energy price scenarios, which are discussed in more detail along with energy prices in the next section.

Figure 4-6: Infrastructure costs depending on utilization



Conversion to EUR/kg based on the lower heating value of hydrogen (120 MJ/kg): 3 ct/kWh = 1 EUR/kg

Source: Own calculations based on Oeko-Institut; EWI; FCN 2022, Fraunhofer ISI 2020b, ICCT 2022a

Excursus: Financing via GHG quota

The GHG Emission Reduction Quota[35] obliges distributors of fossil fuels to successively reduce the GHG intensity of energy volumes in road and rail transport. The 7% reduction, which has been in effect since 2022, increases annually up to 25% by 2030[36]. In addition to electricity-based and biogenic fuels (such as green hydrogen, biodiesel or e-fuels), the use of electricity in road transport can be counted towards meeting the target.

The study *Scenarios and Regulatory Challenges for the Deployment of Charging Infrastructure for Electric Cars and* Trucks. (Oeko-Institut; EWI; FCN 2022) determines the revenues of charging infrastructure operators that can be obtained through the sale of GHG emission reduction certificates to fossil fuel distributors. The achievable revenues depend on the GHG emission intensity of the electricity mix and the prices of GHG quota trading. The latter is currently above 250 EUR/t CO_2e and is expected to rise again to amounts above 400 EUR/t CO_2e in the medium and long term due to the increasing ambition level of the GHG quota. Under current conditions, the study indicates revenues for charging infrastructure operators in the range of at least 5 to 10 ct/kWh. These potential revenues are significantly higher than the costs shown in Table 4-4. However, the extent to which the revenues from GHG quota trading benefit the users, e.g., through more favorable charging electricity prices or faster development of the charging infrastructure, is up to the charging infrastructure operators.

4.7 Energy prices

Due to the high mileage in road freight transport, energy costs are the decisive cost factor over the useful life of the vehicles. Electric drives - especially BEVs and O-BEVs - benefit from lower energy consumption compared to vehicles with internal combustion engines (cf. section 4.3). Nevertheless, decisive for the actual economic savings per kilometer are the energy prices that will be called at the charging point, filling station and overhead line in the future compared to predominantly fossil diesel fuels.

As shown in Figure 4-7 energy prices are made up of the following cost components:

- **Supply price:** Wholesale prices for electricity, hydrogen and diesel fuels are based on the energy price forecasts of the 2021 projection report for Germany (Oeko-Institut; Fraunhofer ISI; IREES; Thünen-Institut 2021). In addition, the supply price includes charges for distribution, which are also based on the framework data of the projection report: Grid charges for electricity and transport costs for hydrogen and diesel. In this scenario, the supply price of electricity increases by 8% from 2030 to 2045, while it decreases by 10% for hydrogen in the same period.
- **Taxes, levies, duties and CO_2 price:** Diesel fuels are subject to energy tax and a CO_2 price that rises over the years[37]. The electricity price includes the electricity tax, the Combined Heating Plant levy, the concession levy, the levy for special forms of network use[38] and the offshore network levy. The use of hydrogen has so far been tax-free. To stimulate the establishment of a hydrogen

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[35] § Section 37a-h of the Federal Immission Control Act (BImSchG)

[36] For the calculation of the GHG emission reduction performance, the reference value of 94 g CO_2e / MJ is used in the GHG ratio as the fossil comparative value of well-to-wheel emissions.

[37] The assumed development of the CO_2 price on fuel (BEHG) is shown in Oeko-Institut; Fraunhofer ISI; IREES; Thünen-Institut 2021. The announced emissions trading for the building and transport sector has not yet been taken into account in this study.

[38] Electricity Network Charges Ordinance (StromNEV) - § 19 Special forms of network use

market, the EU Commission proposes only a low taxation of hydrogen[39]. However, should the use of hydrogen in the transport sector become established in the longer term, the introduction of a tax is not unlikely. The price of hydrogen could consequently rise and be higher than the tax-free prices used in the model.

- **Infrastructure levy:** To finance the expansion of new energy infrastructures for electric commercial vehicles, we consider an infrastructure levy in the scenarios. In addition to the pure cost calculation described in Sect. 4.6, margins are considered. For overhead catenary systems, financing through tolls is legally more obvious, as the system is recommended to be allocated to the road and not to the energy system (ICEM 2020). For better comparability with the other energy infrastructures and vehicle propulsion systems, the infrastructure charge is shown throughout this study together with the energy price.

As described in the previous section, uncertainties exist regarding the level of the infrastructure charge to be applied, for example, due to utilization levels that are difficult to weigh. In the scenarios, we therefore distinguish between two price levels for energy prices overall:

- **"Low":** In this scenario, we assume a predominantly cost-based infrastructure levy for the construction and operation of the energy infrastructures. Compared with the cost calculations in Table 4-4 additional margins and low demand buffers are included in the assumed infrastructure charge. The infrastructure charge is kept constant over the modeled period.

- **"High":** This scenario considers a more market-driven pricing. Both green hydrogen and charging electricity at public fast and high-power charging points are likely to be scarce commodities. As a result, the prices demanded may be significantly higher than the cost estimates. These prices also take into account the risk of low demand. At the same time, industry representatives confirm that customers are expected to be willing to accept higher prices. Comparable developments in the passenger car sector also point to high expected prices at fast and high-power charging points, although price sensitivity is likely to be stronger in commercial traffic. In addition, we expect the initially very high infrastructure charge to decline over time. For the comparatively low-cost DCS charging points, we assume a moderate cost degression of 2% from 2030 compared to Figure 4-7 and for the public charging points NCS, CCS and MCS of 5% as a result of increasing utilization.

Especially in the "high" scenario, the charging price differs significantly for the different charging point types. Based on the data presented in Sect. 4.5.2, a weighted average electricity price per BEV and user profile is calculated. For example, for a BEV400 tractor-trailer with 120,000 km annual mileage, the distribution is approximately 50% depot charging (DCS), 25% public overnight charging (NCS), and 25% public megawatt charging (MCS).

The assumed charging rates for MCSs significantly exceed previous studies (cf. ITF 2022). The aim is to map the market potential of electric commercial vehicles robustly against different energy price levels. In fact, electricity prices in particular could be significantly more favorable for trucking companies and other businesses. For example, self-supply with photovoltaic systems or wind turbines (in conjunction with other partners) offers potential for lowering electricity prices at the depot. The more favorable charging options develop in the depot, the greater the price pressure on public charging power supply is likely to be in order to achieve a cost-covering minimum utilization of the charging points.

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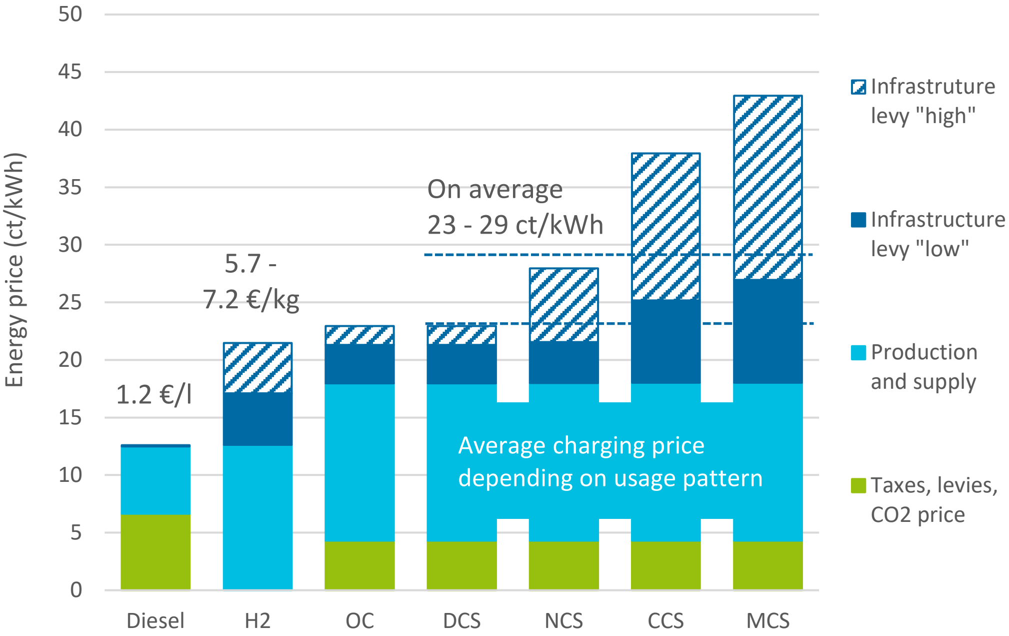
[39] Revision of the Energy Taxation Directive (ETD), Fit for 55 Package, 14.07.2021

Figure 4-7: Energy prices at charging point, refueling station or overhead line in 2030 (in EUR-2020).



DCS: Depot Charging System, NCS: Night Charging System, CCS: Combined Charging System, MCS: Megawatt Charging System, OC: Overhead catenary.

Source: Own calculations based on Oeko-Institut; Fraunhofer ISI; IREES; Thünen-Institut 2021

Excursus: Supply chains for green hydrogen

Various pathways are theoretically possible for supplying a refueling station network with green[40] hydrogen. The generation costs of the renewable electricity, the investment and financing costs of the production plants, the utilization of the electrolysis plants and the transport costs are decisive for the economic viability, as shown in more detail below. The costs listed do not include margins for the provision of hydrogen. In addition, possible subsidies, such as those provided by the *Inflation Reduction Act in the* USA, and the resulting cost reductions in hydrogen production are not taken into account.

- **On-site production in the vicinity of the refueling station:** An obvious option is to set up the electrolysis plant directly with the renewable power source in the vicinity of the refueling station. This saves the transportation of the hydrogen. The study *Hydrogen and hydrogen-based energy carriers or* raw materials. (Oeko-Institut 2020a) shows the influence of electricity production costs and full load hours of the electrolysers on the production price of hydrogen: In the ideal case of favorable solar and wind sites with electricity production costs of 3 ct/kWh and 1,000 to 2,000 full load hours per year, supply costs of hydrogen of 2.50-3.50 EUR/kg can be achieved (without grid connection). This includes already assumed cost degressions for the plants until 2030 ("continuity" scenario). If the filling station location offers less favorable conditions for renewable electricity, the costs will be higher. The highest possible utilization of the electrolysers can alternatively be

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[40] Hydrogen produced via electrolysis plants from additional renewable electricity and fresh water is referred to as "green."

achieved by connecting them to the grid[41]. Due to grid charges and the higher wholesale price for electricity, production costs increase. In this case, a study by the ICCT determines supply costs of hydrogen of 6.41 EUR/kg including compression to a pressure of 700 bar (ICCT 2022b, ICCT 2022d). Furthermore, for grid supply, it must be ensured that additional renewable energy capacities feed into the power system.

- **Off-site production at favorable locations:** Centralized production of hydrogen benefits from economies of scale of larger plants and, above all, the choice of a favorable location for electricity and water supply. According to Oeko-Institut 2020a hydrogen can be produced for 2-3 EUR/kg at good sites abroad with electricity supply costs of 2-3 ct/kWh and with electrolysis utilization rates of 3,000 to 6,000 hours per year (in 2030 in the "continuity" scenario). The study points out that at international sites, higher financing costs could partially offset the better site conditions. In any case, centralized production requires distribution to the refueling stations and very likely transport over longer distances to Germany or Central Europe.

- **Transport by pipeline or ship:** For transports over longer distances, pipelines and/or ship transports can be considered. The cheapest transport option is the use of existing, converted natural gas pipelines (Oeko-Institut 2021) . However, the authors point out that, looking ahead to 2030, only 3% of the generation potential with H_2 supply costs up to 3.50 EUR/kg is within the EU natural gas grid. The cost of transporting gaseous hydrogen in new pipelines is given by the study as about 0.35 EUR/kg per 500 km transport distance. Transport by ship makes liquefaction likely due to the low density of hydrogen, which requires about one-third of the energy content (Oeko-Institut 2020a). Alternatively, hydrogen can be transported via downstream products that are liquid at ambient conditions (e.g., ammonia or methanol) or bound in other carrier media (LOHC: Liquid Organic Hydrogen Carriers). Including conversion, reconversion, and storage, the cost of sea transport up to 3,000 km is 1.75-2.25 EUR/kg (Oeko-Institut 2021). The lower production costs at favorable locations are thus offset by the transport costs incurred.

- **Transport by truck:** Distribution over regional distances to refueling stations is currently mostly carried out by road using gas trailers. Gas container trailers now hold about one ton, and liquid H_2 trailers can transport about four tons of hydrogen. (CAM 2020). By comparison, a diesel trailer can hold around 20 tons of diesel.

The overview shows that there are still some uncertainties with regard to the expected costs of green hydrogen. The assumption of supply costs of 4.20 EUR/kg in 2030, as used in this study, is possible against the background outlined, but must also be classified as rather optimistic. If the refueling costs are included in the balance, hydrogen prices at the tap of less than 4 EUR/kg in the period up to 2030 are hardly feasible without subsidies. The scope for possible tax revenues from the use of hydrogen, as already established for fossil fuels and electricity, is correspondingly small.

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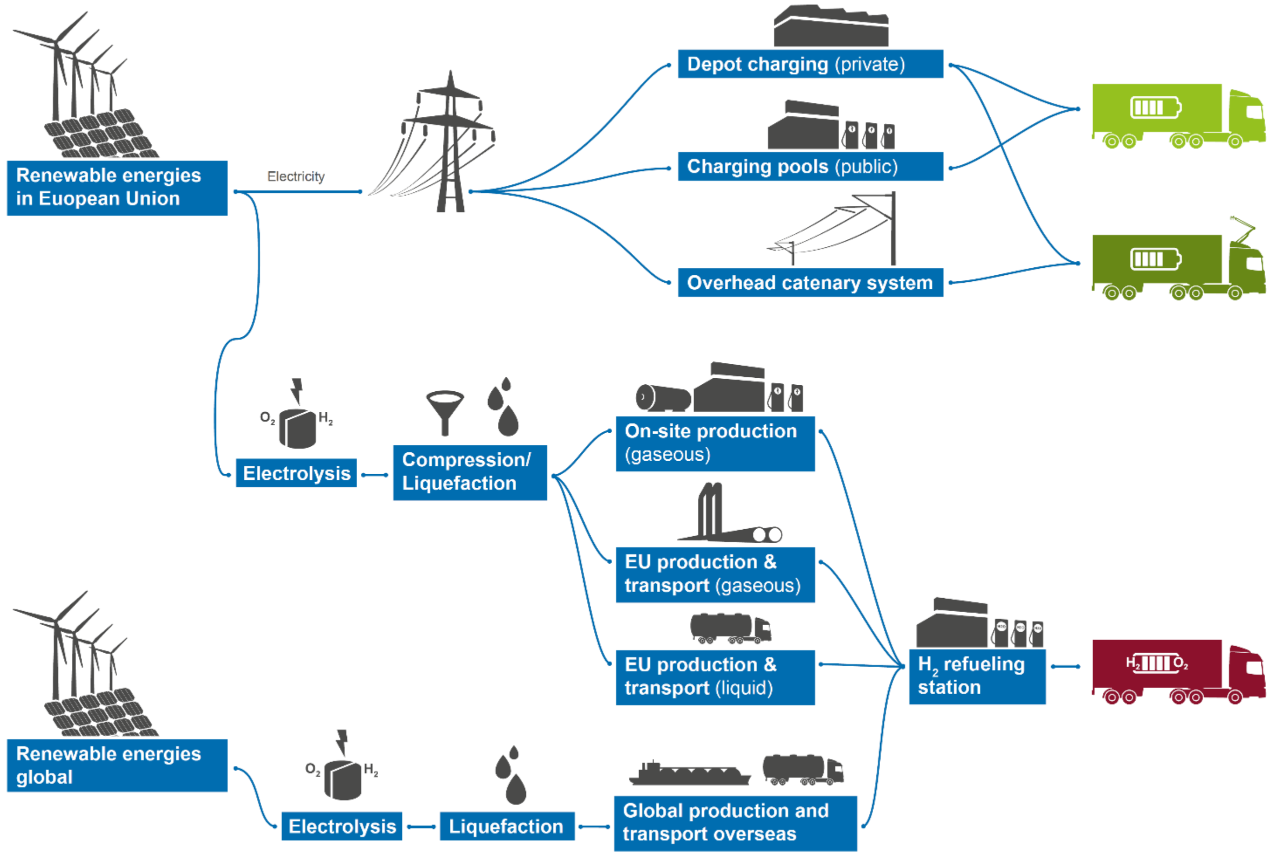
[41] Two delegated acts and their implementation in the 37th BImSchV define the framework conditions under which hydrogen with electricity drawn from the grid is considered green hydrogen.

Figure 4-8: Schematic representation of supply chains for charging stations, overhead lines and hydrogen refueling stations.



Source: Own representation

4.8 Energy infrastructure needs

For the planning and development of charging infrastructures for heavy-duty vehicles, it is crucial to have a demand assessment that is as robust and detailed as possible. As described in Sect. 4.5.2 the KiD2010 survey (BMVI 2010) was used as the basis for the usage distribution of charger types in various infrastructure scenarios. On this basis, demands of public and private charging infrastructure can be determined with the help of market ramp-up modeling.

Using market ramp-up modeling with TEMPS, the electricity demand per charger type is calculated on a national level. To determine the number for charging points required, the total electricity demand is distributed regionally across hypothetic charging pool locations. In addition, the capacity factor at the respective charging points is needed. This is done via three steps, which are presented in the following.

For the regional distribution of total electricity demand, the *Synthetic European road freight transport flow* dataset prepared by Fraunhofer ISI in 2021 is used (Speth et al. 2022). This comprises transport and traffic volumes on the European freeway network (E-road network) and represents an update and 2021 extension of the data set ETISplus[42] collected by Eurostat in 2010. In a first step, the

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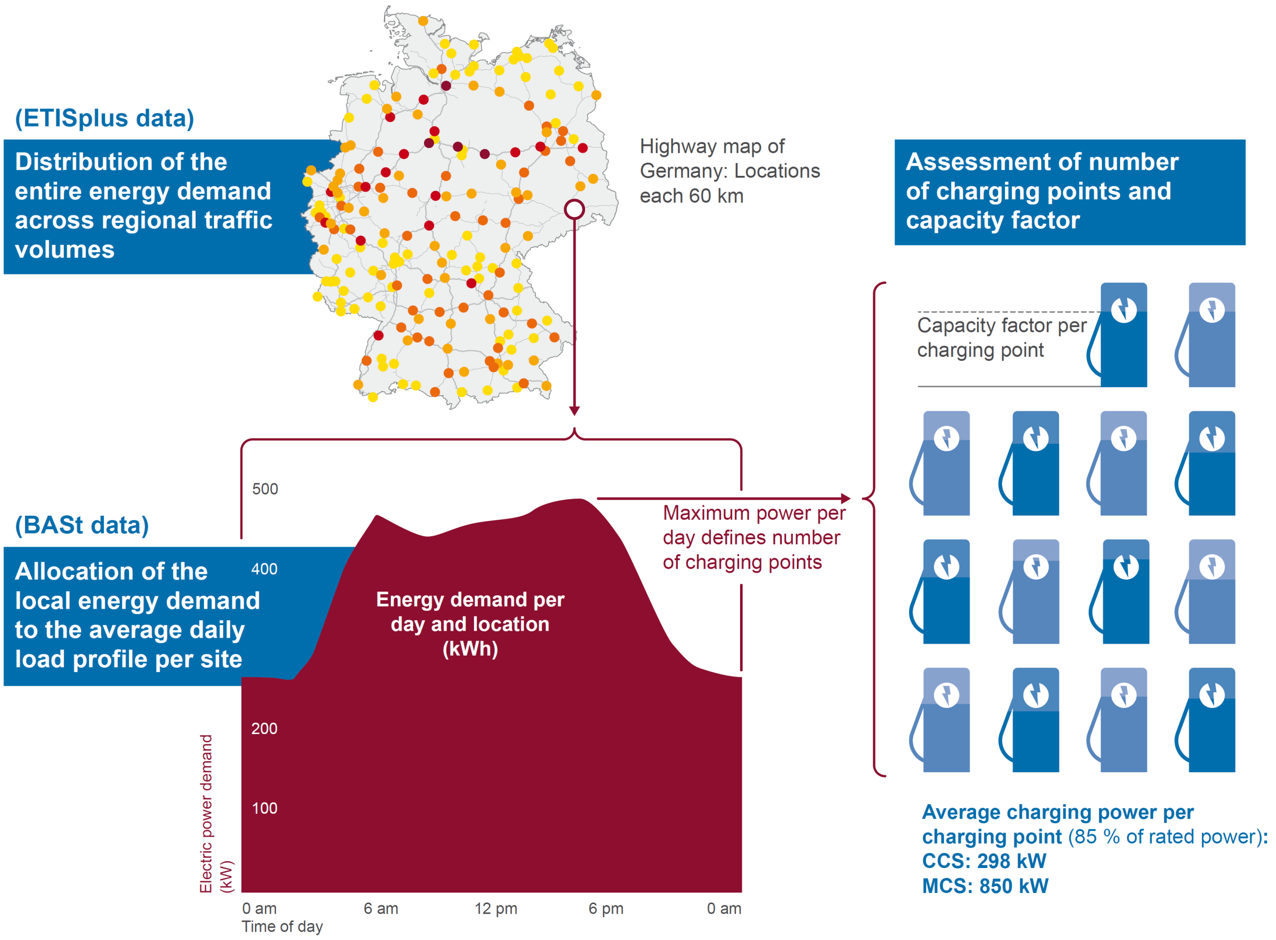
[42] Eurostat, Transport database, 2020. https://ec.europa.eu/eurostat/web/transport/data/database (accessed April 13, 2021).

dataset is used to assign a traffic volume to each section of the federal highway network. Subsequently, the ETISplus data set is intersected with the daily profiles of traffic counting stations available online at the Federal Highway Research Institute (BaSt)[43]. For this purpose, the traffic volumes in ETISplus and in the BaSt data set are divided into five categories. For each category, an average daily profile is formed using the BaSt data set. In this way, a traffic volume and a daily profile can be assigned to each route section.

Figure 4-9: Approach for estimating the demand for charging points along the main traffic axes



Source: Own representation

Following the AFIR (cf. Sect. 3.3), it is assumed in the second step that the locations of the charging sites are located at a distance of 60 km along the highway network. A network algorithm is used to place the locations. A traffic volume and a daily profile can be assigned to each charging pool location using the route segments. Subsequently, the final energy demand from the modeling is distributed across the locations based on the regional traffic volumes. A distinction is already made in the modeling between the different charging point types.

In a third step, the utilization and the number of charging points are determined for each location by allocating the daily energy demand to the daily profiles (see Figure 4-9). For the MCS and CCS fast charging options, the total energy demand at the time of the daily peak is determined. The number

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[43] https://www.bast.de/DE/Home/home_node.html

of required charging infrastructure per location can thus be estimated via the respective charging power. The distribution of the daily energy demand over the number of charging points results in the utilization rate (capacity factor). The calculated utilization thus provides an indicator of how close the daily average is to the load peak of the daily profile.

5 Results of the market ramp-up modeling

This chapter presents the results of the market ramp-up modeling. For all three technology pathways investigated, "BEV", "BEV+FCEV" and "BEV+O-BEV", key boundary conditions are varied in scenarios in order to demonstrate their influence on market ramp-up. The design of the scenarios is described at the beginning for each technology pathway. Subsequently, the modeled total costs of ownership, new registrations and mileage shares of the electric drive options are discussed.

5.1 BEV technology pathway

5.1.1 Scenarios

For the purely battery-electric technology pathway, we consider four scenarios (Table 5-1), in which the following boundary conditions are varied:

- The **availability of charging infrastructure** is a key factor in determining the possible applications of battery-powered trucks. With a fully developed charging network, battery trucks can serve the same user profiles in the scenarios as diesel trucks currently do. Recharging of the battery within the legally prescribed driving breaks is possible on board-scale. We distinguish three time horizons at which the application possibilities for battery trucks are fully given: 2030, 2035 and 2040. Before these time horizons, battery trucks can only be procured in user profiles that are feasible with the charging infrastructure available at the time of vehicle procurement.

- The **charging price** is set to "high" in all purely battery-electric scenarios, i.e. public high-power charging is assumed with prices of up to 42 ct/kWh (in 2030). The high price results from an infrastructure levy that finances the deployment of the charging pools given uncertainties regarding the initial temporal and regional strongly varying utilization of the infrastructure.

- For the **design of the truck toll,** we distinguish between two ambition levels for the national implementation of the Eurovignette Directive (cf. section 3.2): (1) an exhaustion of the scope of the directive, i.e., a 75% reduction of the infrastructure charge for zero-emission vehicles and the introduction of an additional CO_2 component to account for external costs in the amount of 200 €/t CO_2 or (2) a less ambitious design with a 50% reduction for zero-emission vehicles and an additional CO_2 component of 100 €/t CO_2. In both variants, the infrastructure charge[44] included in the toll increases for CO_2-emitting powertrains to compensate for the reductions in order to avoid a shortfall in infrastructure charge revenue. In the modeling, this adjustment is made annually, whereas in practical implementation, an adjustment at the cycle of the infrastructure cost reports in five-year intervals is appropriate. Furthermore, the CO_2-component is collected only when exceeding the CO_2 price on fuel as defined in the Fuel Emissions Trading Act (BEHG) in order to avoid double pricing.

- **Purchase bonuses** are granted in all scenarios for BEVs in the amount of 80% of the additional investment costs for all vehicle purchases and expire in 2024 (as of November 2022).

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[44] The toll includes an "infrastructure levy" to cover the costs of transport infrastructures. The "infrastructure levy" included in the energy price in this study is used to finance the energy supply infrastructures for electric heavy-duty vehicles (charging points, hydrogen refueling stations or overhead catenary systems).

Table 5-1: Design of the scenarios in the "BEV" technology pathway

Scenarios and measures	"recharge2030"	"recharge2035"	"recharge2040"	"rech2035-lowerToll"
Availability of charging infrastructure	From 2030 full demand-based availability	From 2035 full demand-based availability	From 2040 full demand-based availability	From 2035 full demand-based availability
Electricity price at charing point (CP)	"high": market-driven prices at public CP	"high": market-driven prices at public CP	"high": market-driven prices at public CP	"high": market-driven prices at public CP
Truck toll from 3.5 tons GVW	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Lower toll": from 2024: 50% ZEV discount and 100 €/t CO_2 component.
Purchase premiums	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024

Source: Own assumptions

5.1.2 Total cost of ownership (TCO)

In market ramp-up modeling, the total cost of ownership determines the purchase decision and thus the powertrain mix in new registrations. A survey among transport companies in spring 2021 suggests that the TCO is also the most important criterion for new purchases in practice, alongside the considered reliability of the vehicles (Oeko-Institut; Hochschule Heilbronn 2022).

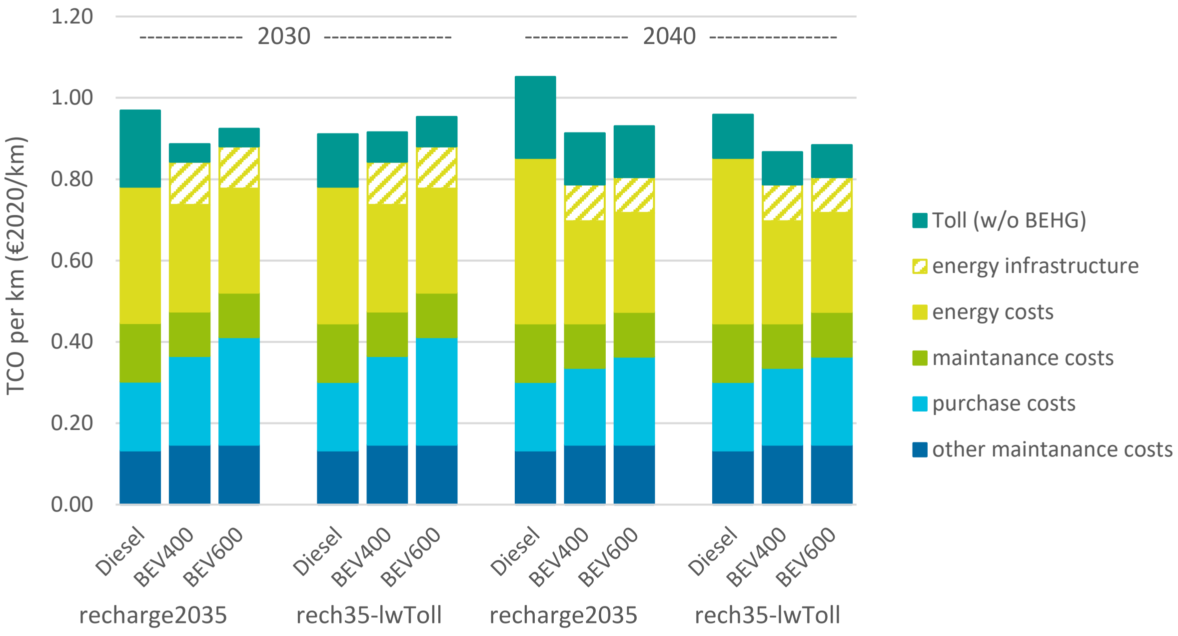
Figure 5-1 shows the average total cost of ownership (including discounting) of a tractor-trailer over a holding period of 5 years using the example of the "recharge2035" and "rech2035-lowerToll" scenarios for an annual mileage of 120,000 km. In the **year of acquisition 2030,** the following results for the individual cost components:

- **Purchase costs:** A battery truck with a range of 400 km (BEV400) is just under 30 % more expensive to purchase than a comparable diesel truck. A higher range of 600 km (BEV600) costs a premium of 55 %.
- **Other maintenance costs:** These include insurance costs, accommodation costs (storage/garage) and fleet management costs. The insurance costs take into account an increased hull component (own damage) resulting from the higher purchase price of battery-powered trucks.
- **Maintenance costs:** The costs for repairs, maintenance and care are assumed to be around a quarter lower for battery-powered trucks because, among other things, there are fewer to no costs for lubricants and urea solution for exhaust gas treatment compared with diesel trucks.
- **Energy costs:** Energy costs account for the highest share of costs in the TCO. The interaction between energy consumption and energy price is decisive for the cost-effectiveness of the vehicle deployment, especially for user profiles with high mileages. The battery truck has an efficiency advantage: the final energy consumption is approx. 50% lower than that of a diesel truck. In the

scenarios considered, this is contrasted by a high charging electricity price and comparatively favorable diesel prices (with low offsetting of external costs). This results in a surcharge for BEV400 of 10 % and for BEV600 - due to a higher share of depot charging - of 7 %. Without taking into account the infrastructure levy for the construction and operation of charging infrastructure, BEVs already achieve advantages in TCO in 2030.

- **Toll:** In the "recharge2035" scenario, the ambition scope of the Eurovignette Directive is fully exploited. The CO_2 differentiation of the infrastructure charge and the additional CO_2 component result in an overall cost advantage of BEV400 and BEV600 compared to diesel trucks. For a weaker CO_2 -differentiation of the truck toll in the scenario "rech2035-lowerToll", the given example shows no advantage in the total costs of battery trucks in 2030.

Figure 5-1: Total cost of ownership (TCO) in the BEV scenarios "recharge2035" and "rech2035-lowerToll" for the acquisition years 2030 and 2040.



User profile: tractor-trailer, 5-year owner period, 120,000 km annual mileage

Source: Own calculations

In the **2040 acquisition year, the** following changes in cost components occur:

- **Purchase costs:** Higher sales volumes for battery-powered trucks have led to cost degression, which is reflected in lower surcharges for new purchases: around 10% for BEV400 and just under 30% for BEV600 compared with the diesel reference.

- **Energy costs:** Via a CO_2 price on fuel of 200 €/t CO_2, the external costs of CO_2 emissions are already included in the diesel price. At the same time, higher demand for public charging electricity has lowered the price at public charging points. The result is savings in energy costs for BEVs of 15%-20% per kilometer.

- **Toll:** The CO_2 component is levied in full on diesel fuel in the scenarios and is therefore included in the energy costs. In 2040, the reduction for zero-emission drives is 50% in both scenarios. The differences between the scenarios with ambitious and less ambitious toll implementation result mainly from the resulting stock of electric vehicles. The fewer diesel trucks in the fleet cede tolls (without reductions), the higher the infrastructure charge per kilometer must become in order to maintain the toll revenue for the infrastructure in total. Accordingly, the reduced tolls for zero-emission drives also increase.

Overall, BEVs are more favorable than comparable diesel trucks in terms of total usage costs in the user profile considered in the acquisition years under consideration. The projections of technology costs and energy prices, among other things, are subject to comparatively high uncertainties. Especially in the early market phase, an ambitious implementation of the truck toll in Germany ensures a robust cost advantage for battery trucks.

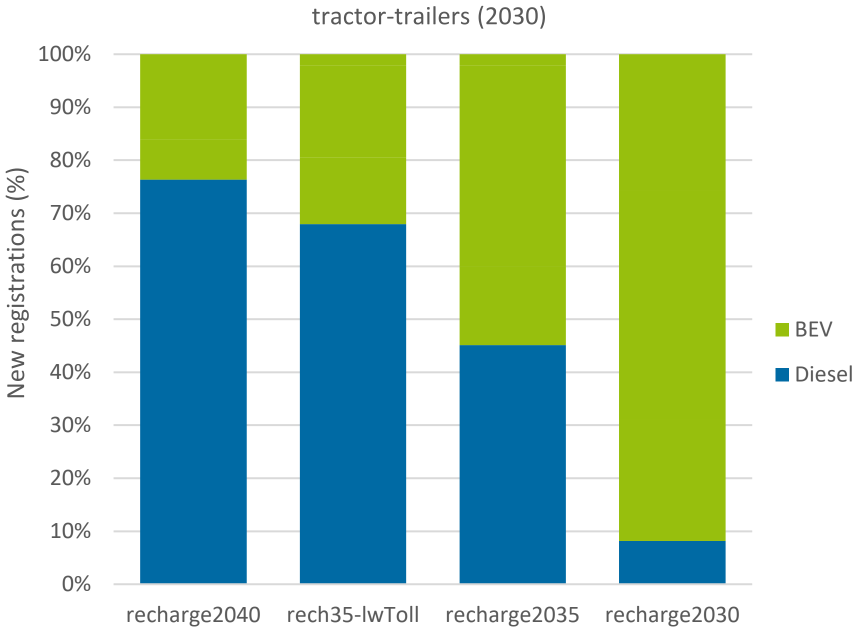
5.1.3 New registrations

The total costs of ownership in the user profiles determine the powertrain mix in the new registrations. In 2030, there are significant differences in the new registration shares of battery-electric trucks in the scenarios considered (Figure 5-2):

- **"recharge2030":** If the development of the charging infrastructure for heavy-duty vehicles takes place at a rate and spread that enables the unrestricted technical use of battery trucks as early as 2030, BEVs will achieve a share of 92% in new registrations in the market ramp-up modeling.
- **"recharge2035"**: If a broad-scale and demand-oriented charging infrastructure is available by 2035, BEVs will develop a market share of 55% in new registrations.
- **"rech2035-lowToll"**: Compared to the scenario with ambitious CO_2 differentiation of the truck toll ("recharge2035"), the economic effect of this instrument on the market share of electric drives becomes apparent. The share of BEVs in new registrations is only 32 %.
- **"recharge2040"**: If sufficient charging infrastructure for limit-free use of battery trucks is not available until 2040 and alternative electric drive options (FCEV or O-BEV) are lacking, only 24% of diesel trucks in new registrations will be replaced by BEVs.

The availability of charging infrastructure and the ambition level of a CO_2 differentiation of the truck toll have a significant influence on the ramp-up of battery-electric trucks. In comparison with the EU Commission's newly proposed targets for CO_2 emissions standards for heavy-duty vehicles, which envisage a 45% reduction in 2030 compared with the reference years (cf. Section 3.1), it is noticeable that the modeled new registration shares of zero-emission vehicles are higher in the "recharge2035" and "recharge2030" scenarios. The CO_2 fleet target values alone do not ensure that a sufficient supply of vehicles is available for the modeled market potential of battery-electric heavy-duty vehicles.

Figure 5-2: New registrations of tractor-trailers in 2030 in the BEV scenarios (varying the availability of charging infrastructure and the ambition level of CO_2 -differentiation of truck tolls).



Source: Own calculations

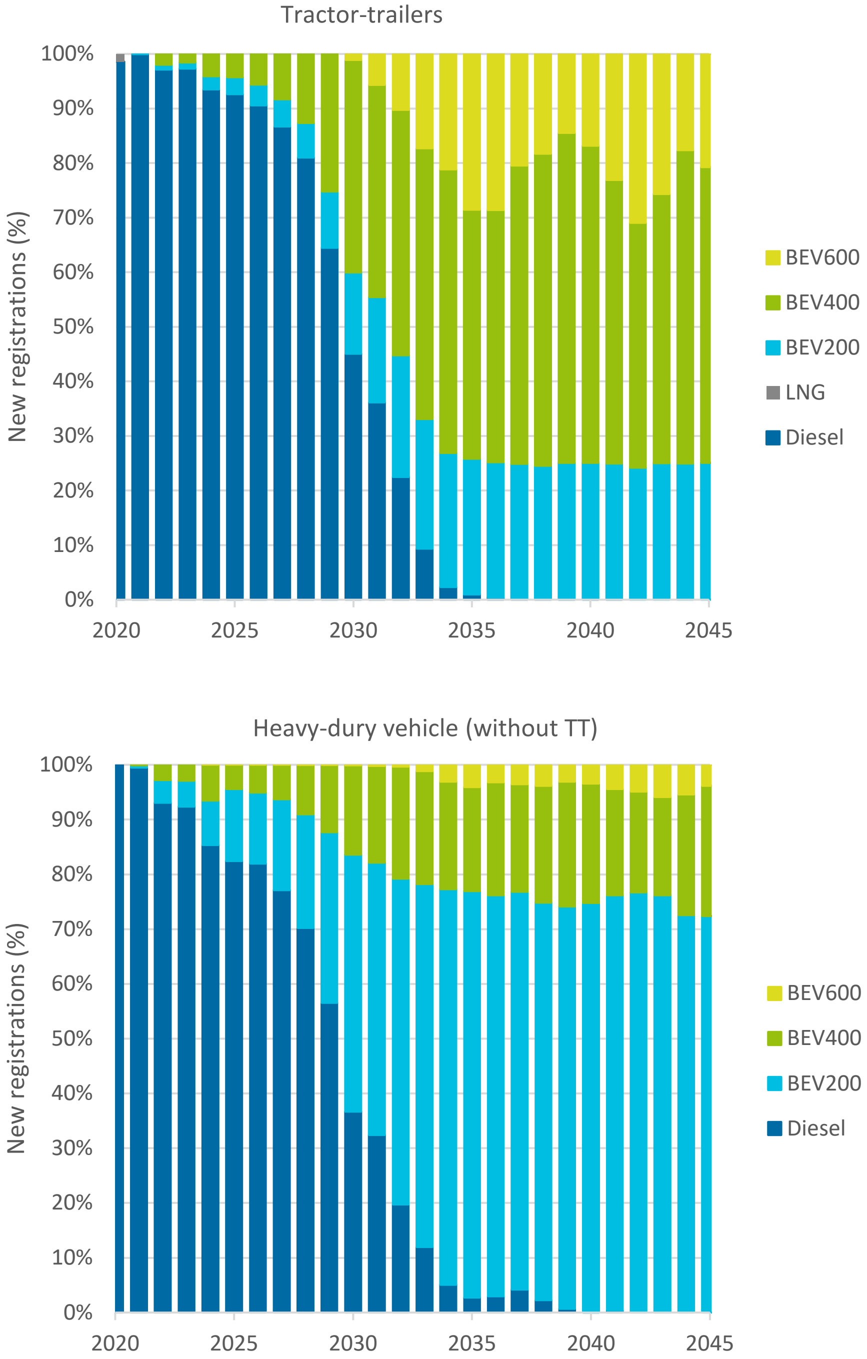
The development of new registrations over time is as follows Figure 5-3 for the "recharge2035" scenario. There are structural differences for the size classes:

- **Tractor-trailers (TT):** In 2035, the ramp-up of BEVs reaches a new registration share of 100%. Most new registrations are BEV400 with a range of 400 km. For BEV600, the market share fluctuates depending on the charging price at public high-power charging infrastructure and the development of battery costs. From 2030 to 2035, cost advantages result from cheaper charging options at the depot. If charging prices become more favorable in an expanded and fully utilized charging network, BEV400s with a lower purchase price will be increasingly favored. The price difference in the purchase price in turn becomes smaller over time due to falling battery costs. In addition, if the TCO are very close (less than 1.5% difference), the drive choice is based on a stochastic function (cf. Sect. 4.1). Strong fluctuations in the time course of new registrations therefore also indicate similar TCO between the drives.

- **Heavy-duty vehicles (excluding TT):** In 2035, almost exclusively BEVs will be newly registered. In these size classes, which statistically have lower range requirements, 75% of new registrations will be BEV200s with a range of 200 km.

In the market ramp-up modeling, BEVs with ranges of up to 400 km are preferentially purchased. Larger battery storage units are more expensive to purchase, but offer greater potential for low-cost charging options in the depot. In the total cost calculation, this results in cost advantages for about 20-30 % of newly registered BEVs.

Figure 5-3: New registrations by powertrain in the "recharge2035" BEV scenario



Source: Own calculations

5.1.4 Stock

New registrations by propulsion system and vehicle survival curves yield the propulsion system distribution in the stock[45]. Figure 5-4 shows that the number of heavy commercial vehicles will

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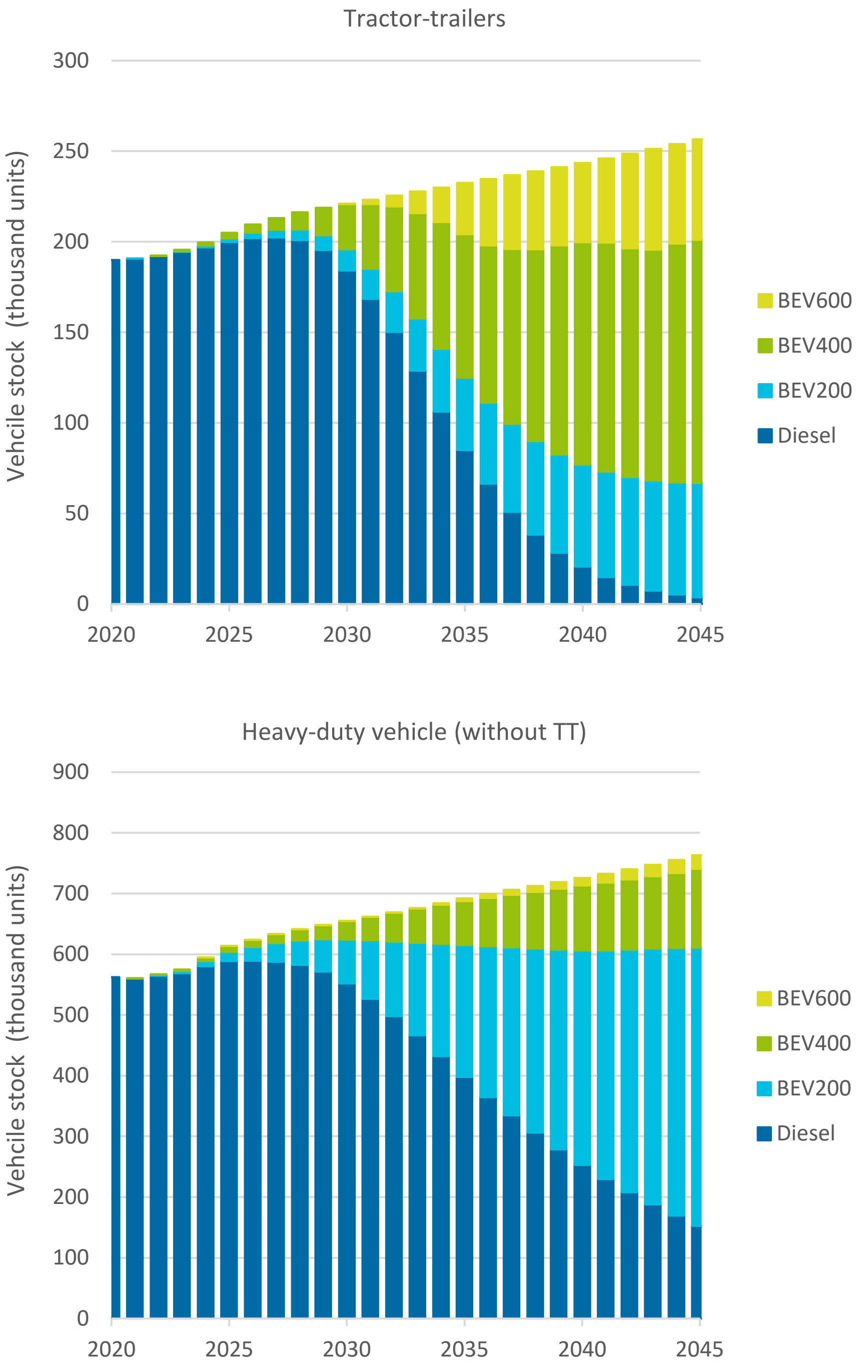
[45] As described in section 4.1 the vehicle stock is modeled on the basis of newly registered vehicles and assumed survival curves of these vehicles. Therefore, the number of vehicles in the inventory may differ from the actual number of vehicles. The new registrations are calibrated to the historical values.

continue to rise in the future. The reason for this is the assumption of increasing demand for freight transport services. As a result, the number of diesel trucks will continue to rise until around 2027, despite the ramp-up of electric trucks.

Figure 5-4: Vehicle stock by powertrain in the BEV "recharge2035" scenario



Source: Own calculations

The following differences emerge for the size classes:

- **Tractor-trailers (TT):** The high annual mileage of tractor-trailers is statistically associated with shorter vehicle lifetimes. The fleet will be fully electrified by 2045.

- **Heavy-duty vehicles (excluding TT):** Although almost exclusively BEVs will be newly registered from 2035, there will be residual stocks of diesel trucks with a share of 15% in 2045. In the modeling, the survival curves of the vehicles were kept constant over the years. In reality, in an increasingly electrified road transport with substantial economic disadvantages for the operation of diesel trucks, the stock in these size classes will probably also be electrified faster than suggested by historical survival curves for diesel trucks.

In total, BEVs account for 16% of the stock in 2030, rising to 48% by 2035.

5.1.5 Electric driving share

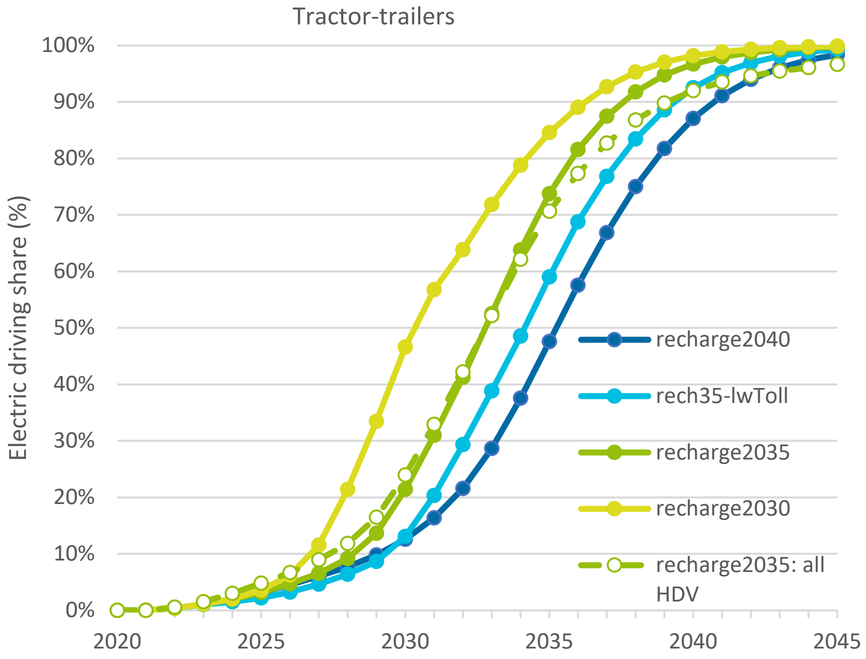
According to the *Climate Protection Program 2030,* the German government's goal is to have one-third of the mileage in road freight transport based on electricity or electricity-based fuels by 2030 (cf. Section 3.4). The goal of climate neutrality by 2045 results in the further goal of achieving an electric driving share of 100 % by 2045 and thus enabling emission-free vehicle operation.

A comparison of the electric mileage shares in the scenarios considered is shown in Figure 5-5 with a focus on tractor-trailers:

- **"recharge2030":** In 2030, an electric driving share of 47% is achieved. The high charging prices at public high-power charging points have a dampening effect on the ramp-up of electric driving performance, which leads to a changed S-curve from the year 2030.
- **"recharge2035**": With an electric driving share of 21% in 2030, the one-third target is missed, but the share is already 31% in the following year. This shows how steep the ramp-up curves must be to achieve the climate protection targets. In this scenario, the ramp-up of electric mileage is essentially slowed down by the (insufficient) availability of charging infrastructure. If all road freight transport, including all heavy-duty vehicles with a gross vehicle weight of 3.5 t or more, is included in the calculation, the share of electric driving reaches 97% in 2045. The residual diesel vehicles described in the previous section therefore contribute only to a very small extent to the total mileage.
- **"rech2035-lowerToll**": In 2030, 13% of the mileage will be electric. Compared to the "recharge2035" scenario, which offers a higher incentive for battery electric vehicles (BEV) through the truck toll, up to 15% less mileage is provided emission-free each year in the period from 2030 to 2035.
- **"recharge2040**": Compared to a faster expansion of the charging infrastructure in the "recharge2035" scenario, up to 25% less driving is done electrically each year.

The climate protection targets of the German government for road freight transport will be achieved in the scenarios if a board-scale and well-performing charging infrastructure is available between 2030 and 2035 and the ambition level for CO_2 differentiation of the truck toll is fully exploited in the national implementation.

Figure 5-5: **Electric driving share in the BEV scenarios**



Source: Own calculations

5.2 Technology pathway: BEV+FCEV

5.2.1 Scenarios

For the combined technology pathway of battery electric vehicles (BEV) and hydrogen fuel cell vehicles (FCEV), we consider four scenarios (Table 5-2), in which the following boundary conditions are varied:

- **Availability of charging infrastructure:** The availability of charging infrastructure determines the achievable market shares of BEVs in the modeling. Due to the high range potential of FCEVs in the order of 1,000 km by 2030, we assume no comparable constraints on FCEV deployment, even if the area coverage of hydrogen refueling stations is assumed to be lower. We vary two charging infrastructure expansion scenarios: full demand-based availability by 2035 and by 2040.

- **Charging electricity price / hydrogen price:** The interaction of energy prices significantly determines the TCO of FCEVs compared to BEVs. The focus of the scenarios for the technology mix "BEV+FCEV" is therefore on different combinations of higher market-driven energy prices ("high") and lower cost analysis-oriented energy prices ("low") for charging electricity and hydrogen.

- **Truck toll:** BEVs and FCEVs benefit equally from a CO_2 differentiation of the truck toll. Accordingly, no variations are modeled, but an ambitious implementation of the truck toll is assumed in all scenarios.

- **Purchase bonuses** are granted in all scenarios for BEVs and FCEVs in the amount of 80% of the additional investment costs for all vehicle purchases and expire in 2024 (as of November 2022).

Table 5-2: Design of the scenarios in the "BEV+FCEV" technology pathway

Scenarios and measures	"recharge2040"	"recharge2035"	"rech2035-lowH2"	"rech2035-lowH2&Ch"
Availability of charging infrastructure	From 2040 full demand-based availability	From 2035 full demand-based availability	From 2035 full demand-based availability	From 2035 full demand-based availability
Electricity price at charing point (CP)	"high": market-driven prices at public CP	"high": market-driven prices at public CP	"high": market-driven prices at public CP	"low": cost-driven prices at public CPs
Hydrogen price at refueling station	"high": market-driven prices	"high": market-driven prices	"low": cost-driven prices	"low": cost-driven prices
Truck toll	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount
Purchase premiums	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024

Source: Own assumptions

5.2.2 Total cost of ownership (TCO)

Differences in TCO result from variations in energy prices in the scenarios considered. In Figure 5-6 the costs for the energy price scenarios "high" ("recharge2035") and "low" ("rech2035-lowH2&Ch") are compared as an example for a tractor-trailer with an owner period of 5 years and an annual mileage of 120,000 km.

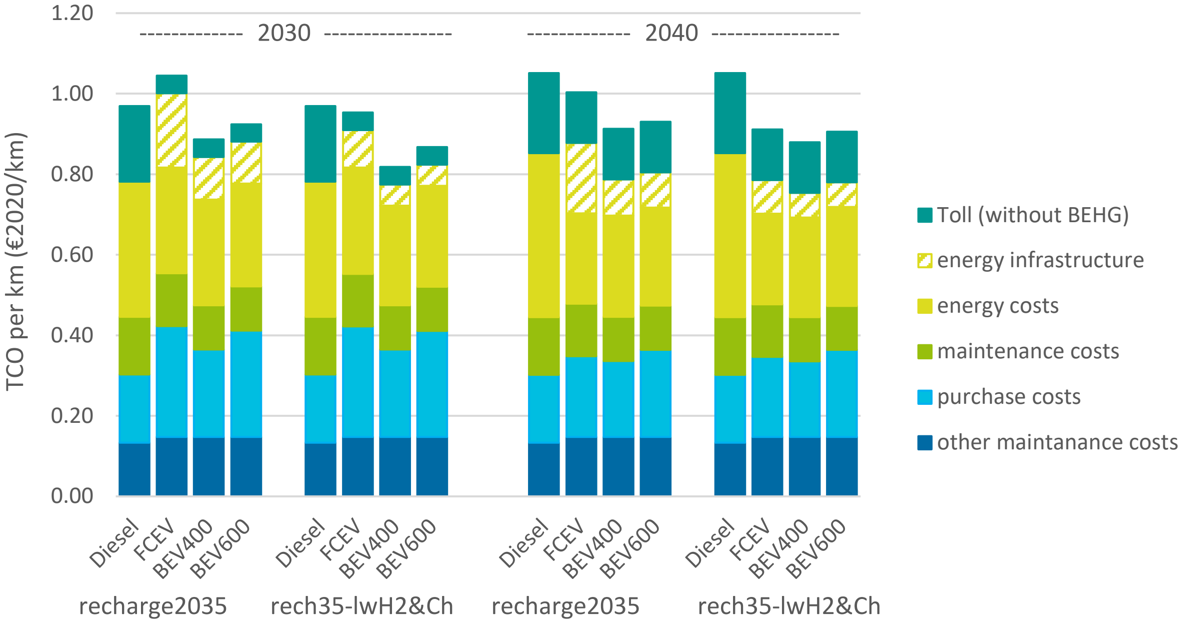
The following relationships emerge for the **2030 acquisition year:**

- **Purchase costs:** For FCEVs, the acquisition costs are at a similar level as for BEV600, namely a 65 % premium over a comparable diesel vehicle. Savings on battery storage are offset by the cost of the fuel cell and hydrogen storage.
- **Other maintenance costs:** For the three electric drives BEV400, BEV600 and FCEV, there is a slight surcharge due to a higher comprehensive insurance premium.
- **Maintenance costs:** For FCEVs, slightly higher repair and maintenance costs are assumed for the maintenance of the fuel cell than for BEVs. Regarding TCO, the differences are negligible.
- **Energy costs:** The efficiency advantage of FCEVs over diesel trucks is lower than for BEVs (50%), with a saving of 15% kilowatt hours per kilometer. If the "high" price scenarios are chosen for both charging electricity and hydrogen ("recharge2035"), FCEVs incur 21-24% higher energy costs than BEV400 and BEV600. Lower hydrogen and charging electricity prices in the "rech2035-lowH2&Ch" scenario reduce energy costs for FCEVs and BEVs, while maintaining the energy cost

advantage of BEVs in the user profile shown. With and without consideration of an infrastructure levy for the construction and operation of charging and hydrogen refueling station infrastructures, FCEVs feature the highest TCO among all powertrain options in 2030.

- **Truck toll:** Despite toll reductions, FCEVs only achieve cost advantages compared to diesel trucks in the case of favorable hydrogen prices.

Figure 5-6: TCO in the "BEV+FCEV" scenarios "recharge2035" and "rech2035-lowH2&Ch" for the acquisition years 2030 and 2040.



User profile: tractor-trailer, 5-year owner period, 120,000 km annual mileage

Source: Own calculations

The following significant changes result for the **acquisition year 2040:**

- **Purchase cost:** the additional investment for electric tractor-trailers falls to 20% for FCEVs, 12% for BEV400s, and 30% for BEV600s in 2040.
- **Energy costs:** In the case of high hydrogen prices, the energy costs of FCEVs fall just below the energy costs for comparable diesel trucks. In the case of favorable hydrogen and charging electricity prices, BEVs and FCEVs achieve cost savings of around 25 % compared with diesel trucks and are at a comparable level in terms of overall usage costs.

The lower efficiency advantage of FCEVs compared to diesel trucks increases the dependence of the total cost of ownership on energy prices compared to BEVs. In 2030, hydrogen prices at the level of the "low" price scenario are needed to achieve cost parity with diesel trucks.

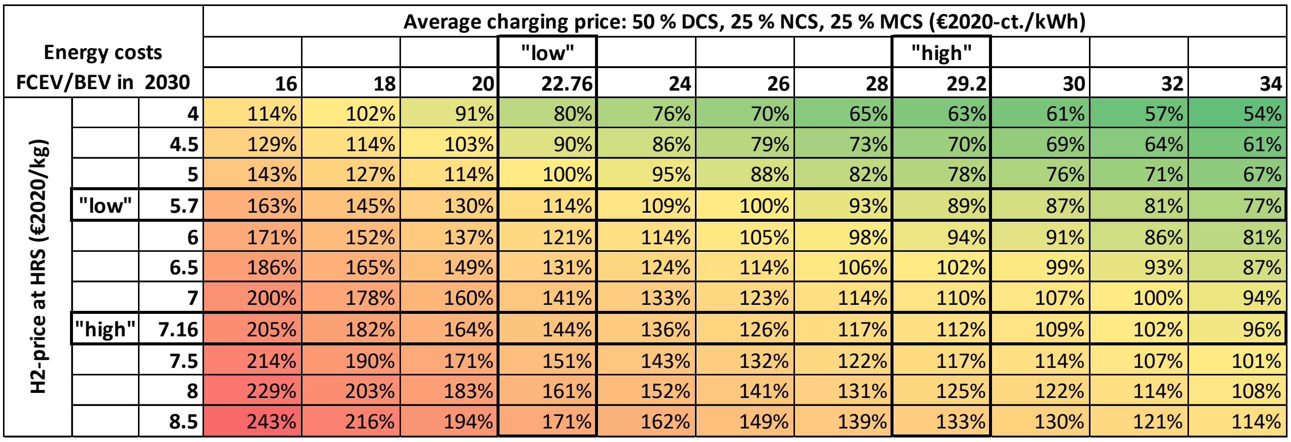
Energy price projections are subject to high uncertainties for both green hydrogen and high-power charging point prices, as no established market exists yet. The impact of price ranges on the ratio of energy costs of FCEVs to BEVs is illustrated in Figure 5-7. In addition to the energy prices used in the scenarios ("low" and "high"), a broader price spectrum is listed. For the charging prices an average charging price is assumed in each case as a mix of 50% depot charging (DCS), 25% public overnight charging (NCS), and 25% megawatt charging (MCS). When charging losses are taken into account, the ratio of energy consumption of BEV to FCEV amounts to about two-thirds. In addition, it should be noted that electricity prices include taxes, surcharges and levies of 4.3 ct/kWh, while the use of hydrogen for energy has so far been tax-free.

From the comparison of energy costs follows:

- **Hydrogen price "high"**: A hydrogen price of 7.16 €/kg only leads to more favorable energy costs of FCEVs per kilometer in combination with average charging electricity prices of 34 ct/kWh. In the "high" energy price scenario, only moderate cost degressions are assumed for the infrastructure-related costs of hydrogen supply (delivery, conversion and refueling). For charging electricity prices, an uncertainty regarding the initial utilization of charging stations is priced in for "high." Similar to public car fast charging points, market players are expected to be more willing to pay for faster recharging options in this scenario.

- **Hydrogen price "low"**: A hydrogen price of 5.70 €/kg achieves parity in the energy costs of FCEVs and BEVs under the set assumptions, if charging electricity prices average 26 ct/kWh. In this energy price scenario, strong cost degressions for production, delivery, conversion and refueling of green hydrogen are already assumed (1.49 €/kg in 2030). From today's perspective, more favorable prices are only realistic in the event of a breakthrough in technology development (cf. Sect. 4.7). Premiums for public high-power charging compared to commercial depot charging prices are expected to depend on the market structure and business models of the companies and less on the actual costs of infrastructure provision (cf. Section 4.6).

Figure 5-7: Ratio of energy costs of FCEV to BEV in 2030 for different energy prices at the refueling and charging stations.



Energy costs FCEV/BEV in 2030			Average charging price: 50 % DCS, 25 % NCS, 25 % MCS (€2020-ct./kWh)										
						"low"				"high"			
			16	18	20	22.76	24	26	28	29.2	30	32	34
H2-price at HRS (€2020/kg)		4	114%	102%	91%	80%	76%	70%	65%	63%	61%	57%	54%
		4.5	129%	114%	103%	90%	86%	79%	73%	70%	69%	64%	61%
		5	143%	127%	114%	100%	95%	88%	82%	78%	76%	71%	67%
	"low"	5.7	163%	145%	130%	114%	109%	100%	93%	89%	87%	81%	77%
		6	171%	152%	137%	121%	114%	105%	98%	94%	91%	86%	81%
		6.5	186%	165%	149%	131%	124%	114%	106%	102%	99%	93%	87%
		7	200%	178%	160%	141%	133%	123%	114%	110%	107%	100%	94%
	"high"	7.16	205%	182%	164%	144%	136%	126%	117%	112%	109%	102%	96%
		7.5	214%	190%	171%	151%	143%	132%	122%	117%	114%	107%	101%
		8	229%	203%	183%	161%	152%	141%	131%	125%	122%	114%	108%
		8.5	243%	216%	194%	171%	162%	149%	139%	133%	130%	121%	114%

The ratio of BEV to FCEV energy consumption is 2/3, taking charging losses into account.

The charging price includes taxes, surcharges and levies of 4.3 ct/kWh; hydrogen has so far been tax-free.

Source: Own calculations

The comparison of energy costs as a function of energy prices is intended to illustrate the relationship between the energy price sensitivities of FCEVs and BEVs, which is important for overall user costs. In practice, more diverse usage patterns exist. For example, charging prices differ depending on the use of different charger types, and the share of energy costs in total usage costs varies depending on mileage. In market ramp-up modeling, these complex relationships are better represented for the overall market. However, due to the extensive calculations per scenario, only a few combinations of boundary conditions can be modeled.

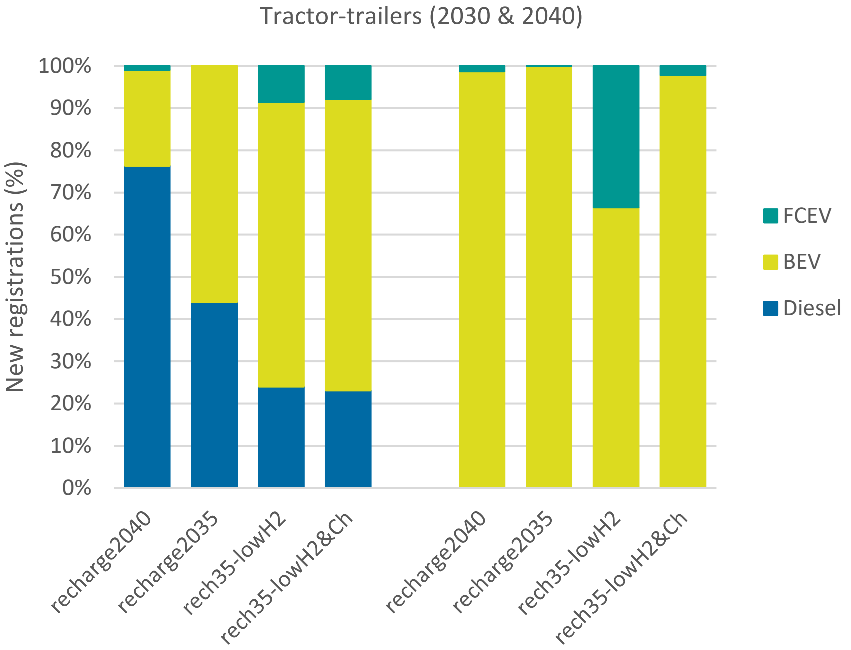
5.2.3 New registrations

The total costs of ownership in the 1552 modeled user profiles (cf. Sect.4.4) result in the new registration structure. Figure 5-8 shows exemplary the relative new registrations by drive system for tractor-trailers in 2030 and in 2040. For sake of clarity, BEVs with different ranges (BEV200, BEV400, BEV600) are shown together. The shares of BEV configurations remain at a similar level as for the purely battery-electric scenarios described above.

The following differences should be highlighted in the scenarios considered:

- **"recharge2040":** In this scenario, deployment restrictions of BEVs are still high due to a lack of availability of charging infrastructure in 2030. FCEVs do not enter the market due to economic disadvantages. As a result, zero-emission drives together only achieve a share of 24% of new registrations. In 2040, the deployment restrictions for BEVs are removed and ZEVs achieve 100% of new registrations.
- **"recharge2035":** The new registration structure essentially corresponds to the purely battery-electric "recharge2035" scenario. FCEVs practically do not enter the market until 2045 due to the higher energy costs.

Figure 5-8: New registrations of tractor-trailers in 2030 and 2040 for the "BEV+FCEV" scenarios (variation of charging infrastructure availability as well as hydrogen and charging prices).



Source: Own calculations

- **"rech35-lowH2":** A combination of favorable hydrogen prices at filling stations and high electricity prices at public charging points enables substantial market shares for FCEVs. In 2030, FCEVs reach a share of 14% and around 33% in 2040. Furthermore, additional diesel trucks can be replaced whose user profiles are still subject to deployment restrictions for BEVs. The combined share of BEVs and FCEVs in new registrations is already 76% in 2030.
- **"rech35-lowH2&Ch"**: If the energy price scenario "low" is selected for both hydrogen and charging prices, FCEVs temporarily enter the market and compensate for deployment restrictions of BEVs. In terms of TCO, BEVs are more favorable than FCEVs and accordingly achieve 100% market share in the long term, once deployment restrictions have been overcome through the expansion of the charging infrastructure.

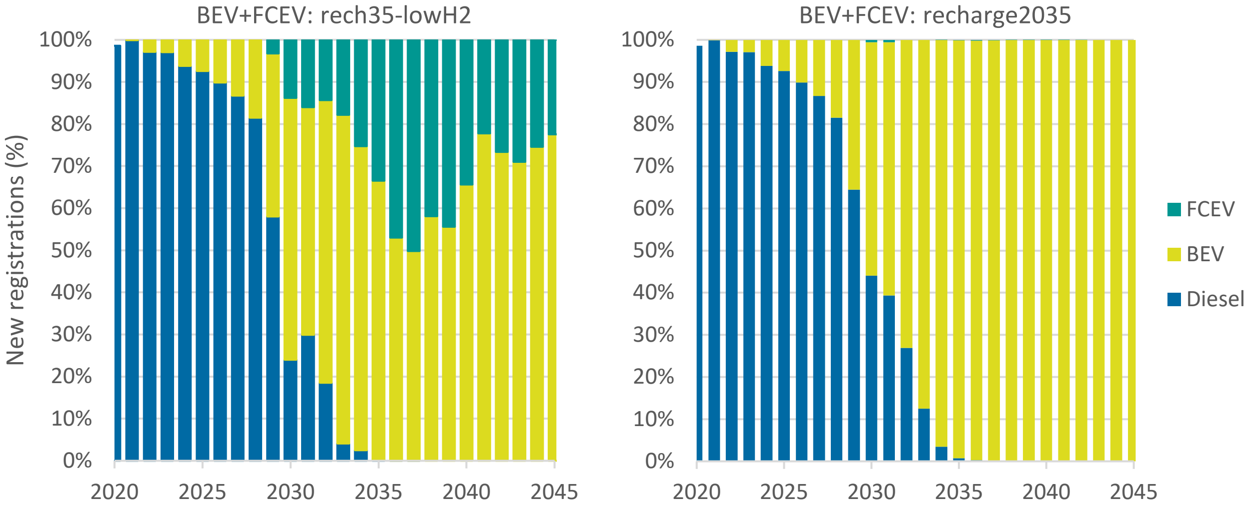
In a technology mix of BEVs and FCEVs, FCEVs can accelerate the electrification of heavy-duty vehicle fleets and secure substantial market shares. The prerequisite for this is a favorable supply of green hydrogen in combination with high charging prices. Nevertheless, in all mix scenarios considered, BEVs dominate market shares in all size classes of heavy-duty vehicles.

We focus on tractor-trailers in the remainder of this discussion, since the share of FCEVs in the other size classes is small (less than 2% market share) and the key relationships for BEVs have already been described for the "BEV" scenarios.

The market ramp-up for the "BEV+FCEV" scenarios "rech2035-lowH2" and "recharge2035", i.e. the direct comparison of a low and high hydrogen price, is shown in Figure 5-9.

- **BEV+FCEV:** The "rech35-lowH2" scenario shows rapid growth of BEVs and FCEVs in the period from 2028 to 2030, which is briefly slowed down by the reduction in the toll reduction from 75% to 50% in 2031 and increases to a 100% share of new registrations in the following years up to 2035. Accordingly, the market share of zero-emission powertrains in the modeling is far beyond the EU's CO_2 fleet target values. In practice, a corresponding supply of BEVs and FCEVs - which is not limited in the modeling - would have to be ensured. In the case of higher hydrogen prices in the "recharge2035" scenario, virtually no new FCEVs are registered over the entire forecast period.
- **FCEV:** The share of FCEVs in new registrations shows slight annual fluctuations in the "rech35-lowH2" scenario, resulting from similar total cost of ownership as BEVs. For TCO with less than 1.5% difference, the drive choice is stochastically distributed in the purchase decision. In the modeling, the decline in market share of FCEVs from 2036 onwards results from falling charging prices as a consequence of high utilization of charging hubs. However, long-term projections especially for energy prices are subject to high uncertainties. In the period from 2035 to 2040, FCEVs achieve market shares of up to 50% in this scenario, which could also prevail in practice in the longer term. However, it should be noted again that only in one of the "BEV+FCEV" scenarios considered are substantial market shares achieved for FCEVs, while in the other scenarios FCEVs have higher overall usage costs than battery trucks and in some cases also than diesel trucks.

Figure 5-9: New registrations of tractot-trailers in the "BEV+FCEV" scenario "rech2035-lowH2" and "recharge2035

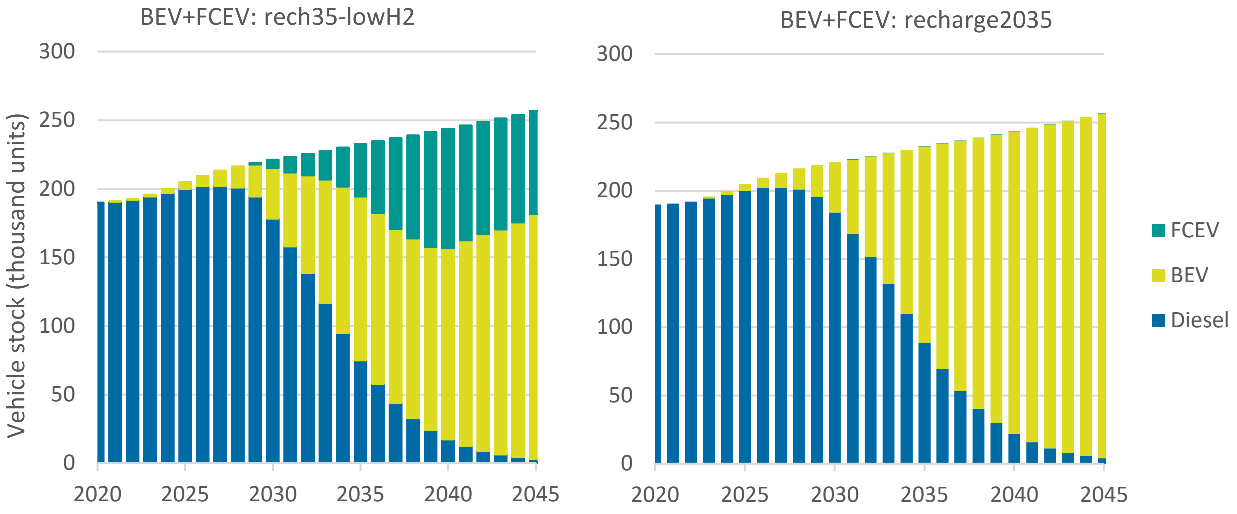


Source: Own calculations

5.2.4 Stock

The stock of tractor-trailers develops in the "BEV+FCEV" scenarios "recharge2035" and "rech2035-lowH2&CH" as in the pure BEV scenario "recharge2035". Essentially, the availability of charging infrastructure determines the diffusion rate of BEVs into the stock, while FCEVs are not in significant demand.

Figure 5-10: Vehicle stock of tractor-trailers in the "BEV+FCEV" scenarios "rech2035-lowH2" and "recharge2035



Source: Own calculations

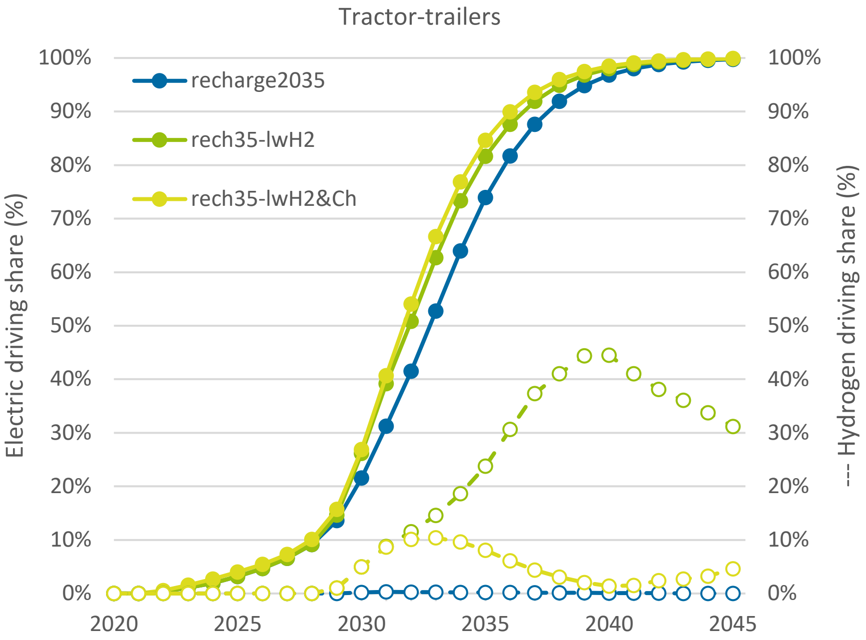
In the "rech2035-lowH2" scenario, a combination of cheap hydrogen prices and expensive charging prices causes a ramp-up of FCEVs in the stock (Figure 5-10). As already described for the "BEV" scenarios, the stock of diesel trucks initially continues to rise until 2027 and falls in the following years to zero trucks and semitrailers in 2045.

In 2030, the share of FCEVs in the stock is 3% and in 2040 around 36%. The share of BEVs in the total stock is significantly higher at 17% in 2030 and 57% in 2040.

5.2.5 Electric driving share

In the electric driving share, the driving performance of BEVs and FCEVs is added up. This implicitly assumes that only electricity-based hydrogen is used in transport. Accordingly, hydrogen or FCEVs can contribute to meeting the German government's one-third mileage target for 2030. Hydrogen from non-electricity-based sources, as in conventional production from natural gas, cannot be counted towards this climate protection target.

Figure 5-11: Electric driving share in the "BEV+FCEV" scenarios



Source: Own calculations

A comparison of the electric driving shares in the "BEV+FCEV" scenarios in Figure 5-11 shows:

- **"recharge2035:** Since there is no demand for FCEVs in this scenario, the electric driving share is congruent with the pure "BEV" scenario "recharge2035". The same applies to "recharge2040", which is therefore not shown for reasons of clarity.
- **"rech2035-lowH2":** In this scenario, up to 10% more mileage is driven electrically each year between 2030 and 2040 than in the "recharge2035" scenario without FCEVs. The share of mileage performed on the basis of hydrogen increases to up to 45%. In 2030, the target of one-third electric mileage is not achieved despite an additional share of 5% by FCEVs.
- **"rech2035-lowH2&Ch":** The course of the electric driving share is similar to the curve in "rech2035-lowH2" and amounts to about 27 % in 2030 (41 % in 2031). In this scenario, up to 10%

of the driving is based on hydrogen in the period from 2030 to 2035. The additional electrification compared to the "recharge2035" scenario is stimulated by more favorable charging prices. In this scenario, too, the share of mileage driven by FCEVs decreases again in the long term.

The electric driving share is a key parameter for the reduction of direct GHG emissions from internal combustion engine vehicles. Favorable energy prices (hydrogen and electricity) accelerate the ramp-up of electrically driven vehicles. However, the limiting factor in the market ramp-up scenarios remains the availability of charging infrastructure in the mix scenarios, since even in a mix of BEVs and FCEVs, the majority of the mileage is provided by BEVs.

5.3 Technology pathway: BEV+O-BEV

5.3.1 Scenarios

For the technology mix of battery and overhead catenary trucks, we restrict ourselves to a consideration of all-electric powertrains. The background is the goal of a complete electrification of road freight transport, which is not fulfilled via overhead hybrid trucks with diesel engines for trips beyond overhead systems.

The following boundary conditions are varied in the BEV and O-BEV technology mix scenarios:

- **Development of charging infrastructure:** The effects have already been shown for the "BEV" and "BEV+FCEV" scenarios. Here, we focus on the "recharge2035" expansion scenario, i.e., from 2035, sufficient availability of charging infrastructure ensures unrestricted use of battery trucks in road freight transport.

Table 5-3: Design of the scenarios in the "BEV+O-BEV" technology pathway

Scenarios and measures	**"rech2035&oc2040"**	**"rech&oc2035"**	**"rech&oc2035-lowCh"**
Availability of charging infrastructure	From 2035 full demand-based availability	From 2035 full demand-based availability	From 2035 full demand-based availability
Availability of overhead catenary (OC) network*	From 2030: 950km, from 2035: 1,900km, from 2040: 3,800km	From 2030: 1,900km, from 2035: 3,800km	From 2030: 1,900km, from 2035: 3,800km
Electricity price at charing point (CP)	"high": market-driven prices at public CP	"high": market-driven prices at public CP	"low": cost-driven prices at public CPs
Truck toll	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount	"Toll": from 2024: 75% ZEV discount and 200 €/t CO_2 component, from 2031: 50 % ZEV discount
Purchase premiums	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024	80 % of the additional investment costs until 2024

Source: Own assumptions

- **Development of overhead line network:** A distinction is made between two development scenarios: (1) a core network of 3,800 km of overhead contact line infrastructure is developed on the main corridors of long-distance road freight transport in Germany by 2040, with 950 km already electrified by 2030, and (2) the core network is completed as early as 2035, with 1,900 km of freeway sections already electrified by 2030.

- **Charging price:** As before, a distinction is made between the two price levels "high" and "low" at charging points. In the analysis, the electricity price at the overhead line corresponds to the price level of depot charging points and includes a fee to refinance the infrastructure construction.[46] Since the construction and financing of the overhead line infrastructure would have to be organized by the state according to current knowledge, price-driving risk margins are rather unlikely. We therefore assume a constant electricity price at the overhead line in the scenarios.

- $_2$**Truck toll:** BEVs and O-BEVs benefit equally from a CO_2 differentiation of the truck toll. Accordingly, no variations are modeled, but an ambitious implementation of the truck toll is assumed in all scenarios.

- **Purchase bonuses** are granted in all scenarios for BEVs and O-BEVs in the amount of 80% of the additional investment costs for all vehicle purchases and expire in 2024 (as of November 2022).

5.3.2 Total cost of ownership (TCO)

The TCO in the "rech&oc2035" scenario and the variant with more favorable charging prices "rech&oc35-lowCh" are displayed in Figure 5-12 for the example of a tractor-trailer with an owner period of 5 years and an annual mileage of 120,000 km. The TCO is based on the following cost components:

- **Purchase costs:** Overhead catenary BEVs are simulated with ranges of 100 km (O-BEV100) and 200 km (O-BEV200). The small battery storage compared to BEV200 and BEV400 leads - despite the additional pantograph - to lower purchase prices. Compared to diesel, the premium is around 20% in 2030 and 10% in 2040. There are no differences between the scenarios.

- **Other maintenance costs:** The insurance surcharge for the O-BEV is lower than for BEVs, in line with the purchase price. The impact on the total cost of ownership is low.

- **Maintenance costs:** Maintenance and repair costs are about 20% less than for comparable diesel trucks. Maintenance requirements on the pantograph increase the costs slightly in the assumptions compared to BEVs.

- **Energy costs:** The energy consumption of O-BEV is slightly higher than for BEV due to the flow resistance of the pantograph and is approx. 49 % kilowatt hours per kilometer less than for diesel trucks (51 % for BEV200). Due to the favorable electricity price at the overhead line, O-BEVs already achieve 4% lower energy costs than diesel trucks in 2030. In 2040, about 25% of energy

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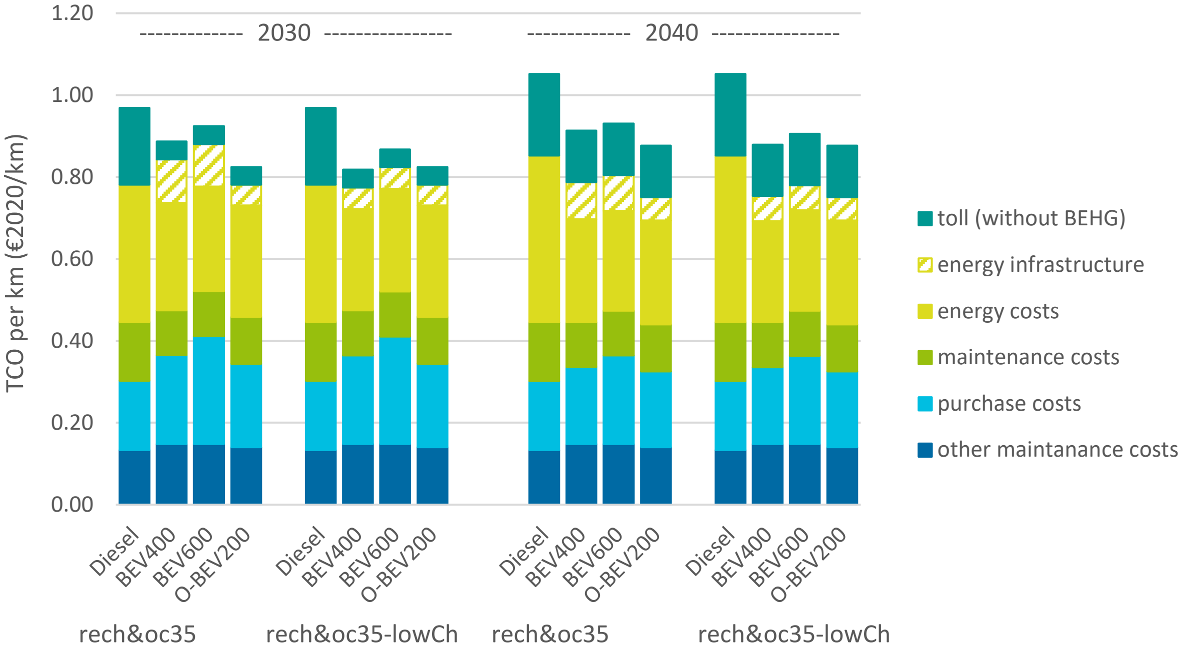
[46] In the present scenarios, the construction of the overhead line infrastructure is ensured via a levy in the electricity price. This creates better comparability with the energy costs of BEVs and FCEVs, which also include corresponding infrastructure charges. Legal opinions recommend refinancing via truck tolls, since the overhead line system is likely to be considered an "accessory to the road" and not to the energy system (ICEM (IKEM 2022)). For the present TCO analyses, the type of allocation makes no difference.

costs are saved. In the "rech&oc2035-lowCh" scenario, the energy costs for BEVs and O-BEVs are at a similar level.

- **Truck toll:** Without considering the truck toll, the TCO for O-BEVs are already at the level of conventional diesel trucks in 2030. The CO_2 differentiation of the toll results in a robust cost advantage for O-BEVs over the period under consideration until 2045.

In the scenarios considered, O-BEVs achieve the most favorable overall TCO. Already in 2030, cost parity with conventional diesel trucks is achieved in the illustrated user profile without a CO_2 differentiation of the truck toll. Compared to BEVs, additional investment in the pantograph is offset by smaller battery storage and possibly cheaper energy prices. If surcharges for public high-power charging are low, O-BEV and BEV400 achieve similar overall usage costs.

Figure 5-12: TCO in the "BEV+O-BEV" scenarios "rech&oc2035" and "rech&oc2035-lowCh" for the acquisition years 2030 and 2040



User profile: tractor-trailer, 5-year owner period, 120,000 km annual mileage

Source: Own calculations

5.3.3 New registrations

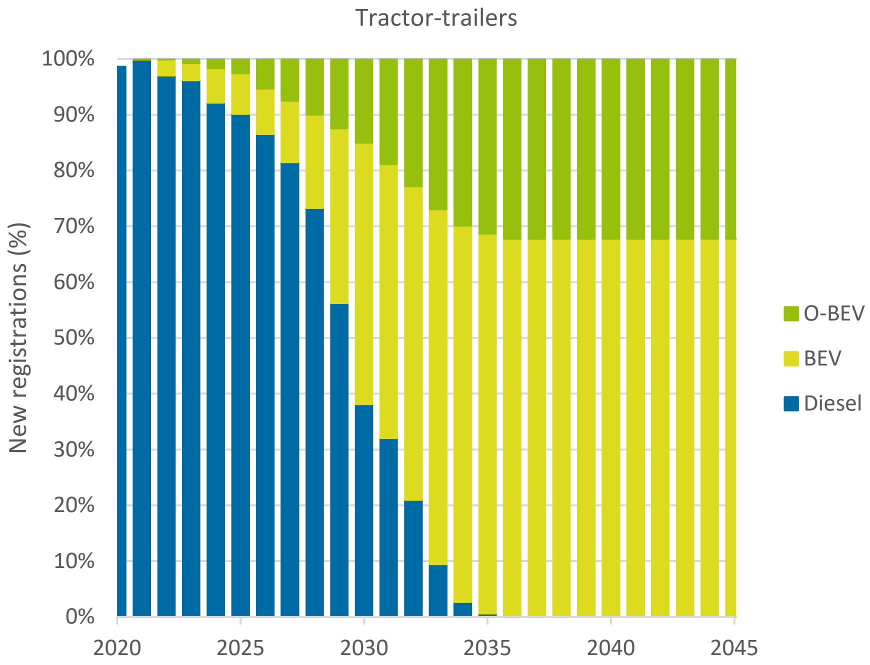
The user profiles for overhead catenary trucks are based on trip data sets from the StratON project. These indicate which trips of heavy-duty traffic (here: vehicles with a gross vehicle weight of 12 tons or more and 4 axles) graze a hypothetical overhead line network, how high the trip share is on this core network, and how high the trip shares are in the up- and downstream sections on the non-electrified routes (cf. Section 4.5.3). The mileage is put in relation to the territorial mileage in Germany, i.e., the mileage generated in Germany. From this, in addition to user profiles for O-BEV, potentials for the deployment of O-BEVs with defined battery range can also be derived. We do not consider the use of hybrid overhead catenary trucks (with hybrid diesel engines), which are not subject to range restrictions, in the scenarios against the background of a required emission-free operation until 2045.

We first look at the development of the new registration structure over time in the "rech&oc2035" scenario, in which both a demand-oriented charging infrastructure and a core network of overhead line infrastructure are available in 2035 (Figure 5-13).

- **BEV+O-BEV:** As soon as the energy infrastructures for O-BEV and BEV are available, the electric drives reach a share of 100 % of new registrations. In 2030, the combined share of BEVs and O-BEVs is 62%, higher than in the BEV-only "recharge2035" scenario (55%). As in the previously discussed scenarios, the share of zero-emission powertrains in 2030 is therefore higher than the CO_2 targets set by the European CO_2 fleet limits for heavy-duty vehicles.
- **O-BEV**: The share of O-BEVs in new registrations increases with infrastructure expansion and saturates at around 32% from 2035. The reason for the saturation is the technical deployment potential, which results for O-BEVs from the required relations up- and downstream of the overhead line network and the available battery storage in the vehicle. Economic advantages of O-BEV fully exploit the technical deployment potential. O-BEVs with a range of 100 km (O-BEV100) and 200 km (O-BEV200) are newly registered in roughly equal proportions.

The estimation of the technical deployment potential is explained in more detail in Sect. 4.5.3. It must be taken into account that the upstream and downstream lengths in the underlying vehicle data set are not limited to territorial shares in Germany, i.e. they arise in part from driving shares abroad. If an overhead catenary network is not only established in Germany, but on the main transport axes in Europe, further user profiles can be covered by O-BEV. In this case, the technical deployment potential of O-BEV increases to around 50 % of the domestic German mileage.

Figure 5-13: New registrations of tractor-trailers in the "BEV+O-BEV" scenario "rech&oc2035".



Source: Own calculations

For the "BEV+O-BEV" scenarios considered, the following differences in the new registration structure result compared to the "BEV" scenario "recharge2035" (Figure 5-14):

- **"rech&oc2035":** In 2030, O-BEVs substitute about 6% diesel trucks in addition to the BEV-only scenario. In addition, 7 % BEVs are replaced by O-BEVs. The share of O-BEVs in new registrations increases from 13 % in 2030 to 32 % in 2040.
- **"rech2035&oc2040":** A slower build-out of overhead infrastructure by 2040 reduces the market share of zero-emission powertrains to 59% and of O-BEVs to 9% in 2030. In 2040, the market conditions are the same as in the case of a build-up by 2035 ("rech&oc2035").
- **"rech&oc35-lowCh":** Favorable charging prices at stationary charging points favor the ramp-up of BEVs. The influence is small in 2030 due to parallel deployment restrictions for BEVs. From 2035, the share of new registrations of O-BEVs saturates at 27%.

The ramp-up of O-BEVs is essentially limited by the availability of the overhead line infrastructure. In addition to the driving options with direct power supply from the overhead line, the ranges achievable away from the overhead line network via the battery storage in the vehicle also play a role here. Especially in combination with high prices at public charging hubs, O-BEVs achieve economic advantages in all feasible user profiles. Uncertainties consequently relate primarily to the deployment potentials that can be achieved depending on the overhead line network. Under the assumed framework conditions, BEVs will dominate new registrations of tractor-trailers in the future.

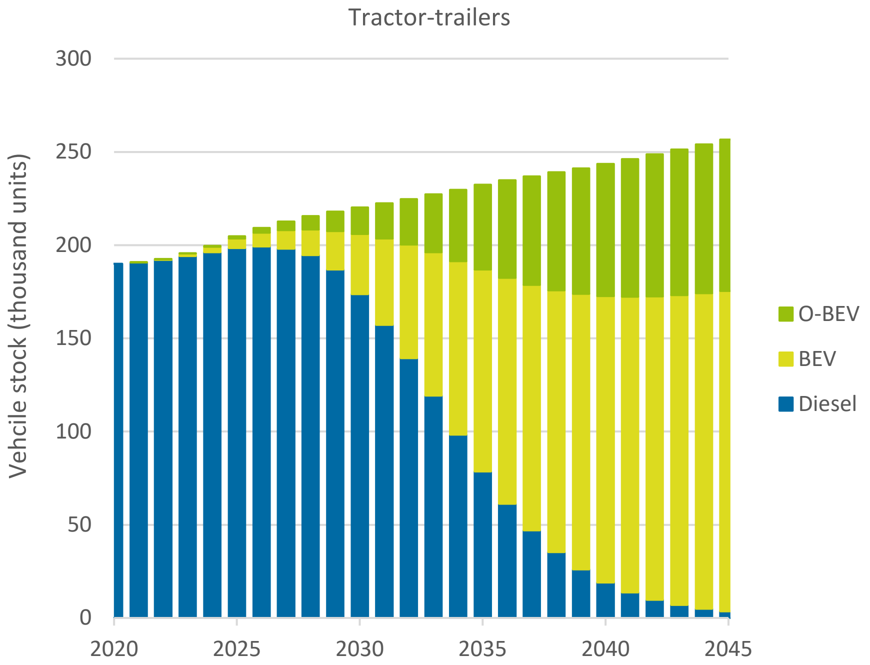
Figure 5-14: New registrations of tractor-trailers in 2030 and 2040 for the "BEV+O-BEV" scenarios (varying the availability of overhead line infrastructure and charging prices at charging hubs).

Source: Own calculations

5.3.4 Stock

The development of the stock of tractor-trailers is shown for the "BEV+O-BEV" scenarios is shown exemplarily for the "rech&oc2035" scenario in Figure 5-15. As already described in Sections 5.1.4 and 5.2.4 the number of tractor-trailers with conventional diesel engines will initially continue to rise to just under 200,000 vehicles by 2027. Subsequently, the number of O-BEVs and BEVs drops to almost zero diesel-powered vehicles in 2045. In the long term, the number of tractor-trailer will consist of 32 % O-BEVs and 68 % BEVs.

Figure 5-15: Stock of tractor-trailers in the "BEV+OC-BEV" "rech&oc2035" scenario



Source: Own calculations

5.3.5 Electric driving share

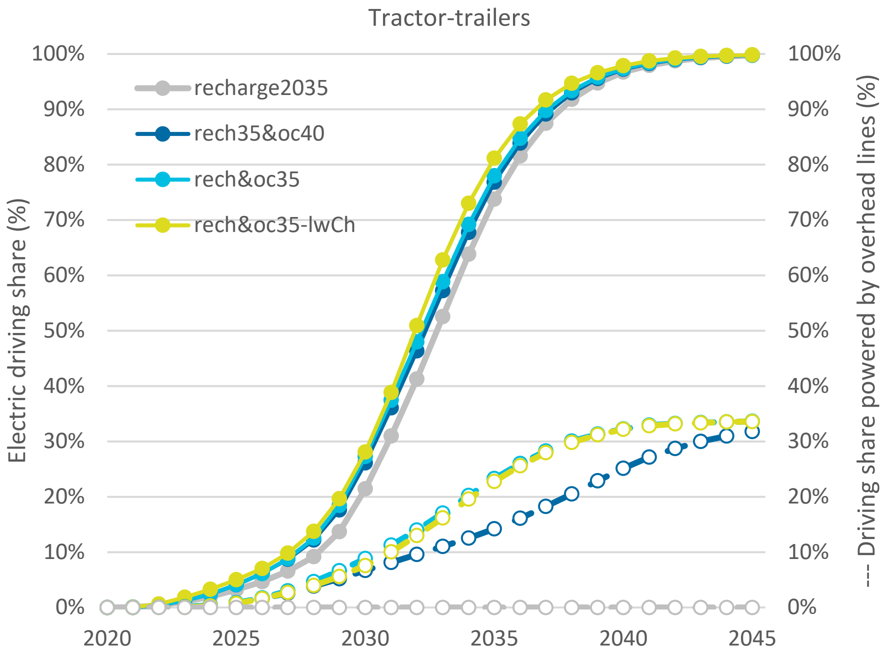
A comparison of the "BEV+O-BEV" scenarios in Figure 5-16 shows:

- **Electric driving share:** The differences between the "BEV+O-BEV" scenarios are small. The one-third mileage target of the federal government is reached somewhat late in 2031. Compared to the pure "BEV" scenario, the electric driving share increases by up to 10% in the period from 2025 to 2040 or electrification accelerates by one to two years.

- **Overhead line driving share:** This includes the power supplied directly from the overhead contact line as well as the power dynamically charged in the battery. In the model, about half of the electricity required for the up- and downstream sections of the OC-network is charged in the depot. In 2045, approximately 34 % of the mileage will be provided by the power supply of trucks and tractor-trailers from the overhead line infrastructure.

A technology mix of BEV and O-BEV accelerates electrification in the scenarios considered only slightly compared to the BEV-only scenario, as both technologies are highly dependent on the availability of the respective energy infrastructures. In perspective, in all "BEV+O-BEV" scenarios, about one third of the electricity demand of tractor-trailers can be covered by the overhead line infrastructure. If, in addition to a core network in Germany, overhead lines are also installed on the main transport axes in Europe, around 50% of the mileage of tractor-trailers can potentially be provided via electricity from overhead lines.

Figure 5-16: Electric driving share in the "BEV+OC-BEV" scenarios



Source: Own calculations

5.4 Direct GHG emissions

This section describes the GHG emissions for the modeled scenarios in more detail. According to official regulations, the transport sector is assigned the GHG emissions from the use of transport modes, the so-called "tailpipe emissions" (UBA 2023a).

Figure 5-17 shows the development of emitted CO_2 equivalents in road freight transport in the most important scenarios. For comparison, the historical GHG emissions are shown as well as a classification in relation to the Federal Climate Protection Act. This sets annual emissions budgets for the transport sector. Road freight accounts for about one-quarter of the transport sector's GHG emissions. While road freight is not assessed separately, a comparison with this share of sector targets is intended to provide guidance on the level of GHG emissions in the modeled scenarios. Therefore, in addition to the modeled emission trajectories, the annual emission budgets reduced by a factor of one-quarter are shown.

In the pre-Corona year 2019, GHG emissions from road freight transport were 46 million tons CO_2e (UBA 2023b). For 2022, CO_2 equivalents are expected to return to pre-Corona levels as the pandemic subsides. In the scenarios, GHG emissions stagnate at about 45 million tons of CO_2e by 2025, as emissions savings are offset by increasing freight traffic. Compared to the hypothetical road freight emissions budget explained above, this results in a gap of 14 million tons CO_2e.

In the further course from the year 2025, the effect of the key levers in the scenarios becomes clear:

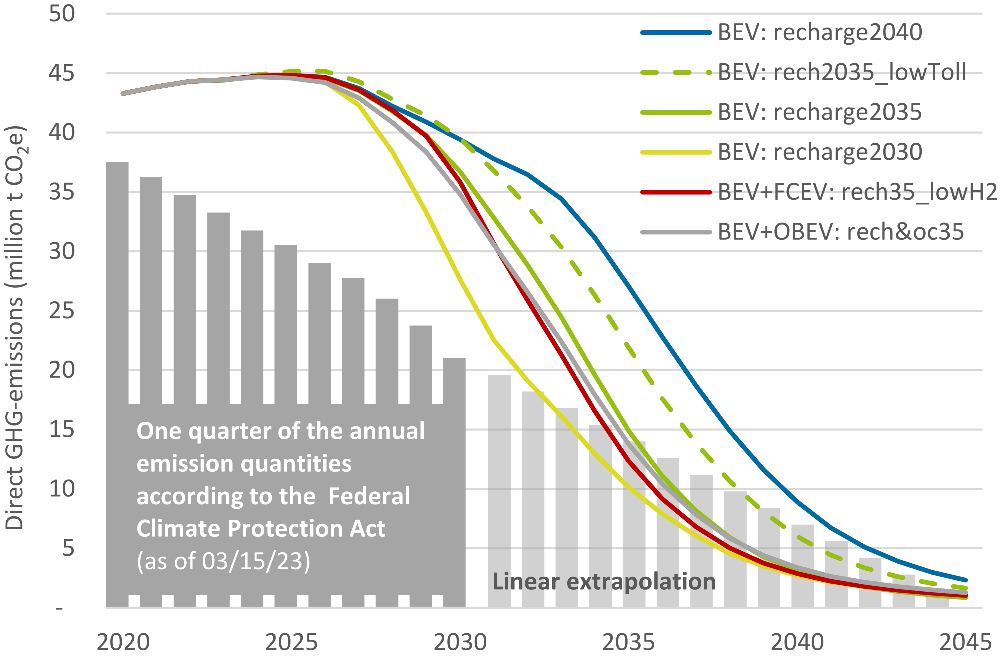
- The **availability of charging infrastructure** has the greatest influence on the development of GHG emissions in road freight transport in the scenarios examined. In 2030, around 25 million tons CO_2 equivalents are emitted in the fastest build-up scenario "recharge2030". This nevertheless leaves a gap to the hypothetical emissions budget of 4 million tons CO_2e. A slower build-up causes significantly higher GHG emissions of 35 million tons CO_2e in the "recharge2035" scenario and 38 million tons CO_2e in the "recharge2040" scenario in the same year.

- An **ambitious CO_2-differentiation of truck tolls** is another important lever to accelerate the electrification of heavy-duty vehicle fleets and reduce GHG emissions in road freight transport. The additional economic potential is shown in comparison to a scenario with only minor deployment restrictions on BEVs ("recharge2030"). In this scenario, GHG emissions in 2030 are almost 14 million tons CO_2e below the scenario with less ambitious CO_2 spreading of the truck toll ("rech35-lowToll").

- Under the conditions of an ambitious CO_2 -differentiated truck toll and a medium-term availability of charging infrastructure, the **technology mix** has only a comparatively small influence on the development of GHG emissions. In 2030, the mix scenario of BEVs and FCEVs (in the case of favorable hydrogen prices) and the mix scenario of BEVs and O-BEVs emit about 2 million tons CO_2e more than the pure BEV scenario "recharge2035".

The contribution of efficiency improvements in diesel engine vehicles is relatively small: energy consumption is reduced by 4% in the modeling compared to 2020 levels. The main driver of GHG emission reductions in the scenarios is the transition to electric commercial vehicles.

Figure 5-17: Direct GHG emissions from road freight transport in the scenarios



Road freight transport currently generates about a quarter of the transport sector's GHG emissions. To evaluate the GHG reductions in the scenarios, the annual emission volumes from KSG 2023 reduced by a factor of one quarter are therefore shown.

Source: Own calculations, UBA 2023b and KSG 2021

If the hypothetical annual emission volumes (by a factor of one quarter) are transferred to road freight transport from 2030 onward and reduced to zero by 2045, the reduction target trajectory will be reached at different times in some scenarios and undercut in subsequent years. Although it is not possible to offset the excess emissions of CO_2 equivalents accumulated up to that point, the differences in net emissions compared with the target path are substantial: in "BEV: recharge2030," a total of 65 million tons CO_2 equivalents of additional emissions, while in the case of slower electrification in the "BEV: recharge2040" scenario, as much as 242 million tons CO_2 equivalents more are emitted than the hypothetical target trajectory specifies. Today's framework therefore has a major impact on the course of GHG emissions from 2030 onwards.

While electrification in the scenarios described leads to a reduction in tailpipe emissions and emissions associated with fuel supply in the upstream chain, the production and disposal of BEVs, FECVs and O-BEVs give rise to higher emissions than diesel trucks, for example, because of the batteries, fuel cells and hydrogen tanks. Furthermore, additional emissions arise in the scenarios from the generation of electricity and hydrogen, as well as from the construction of the energy infrastructure. A complete life cycle analysis is beyond the scope of this study. The literature shows that, as a result, the savings of emission-free electric heavy-duty vehicles in operation clearly outweigh the additional emissions during vehicle production (IFEU 2022a). The development of energy infrastructures is hardly significant in the balance sheet. (IFEU 2022b). The advantages of the GHG balance already arise in the current electricity mix. The lower the GHG emissions of the electricity mix are in perspective, the greater the overall advantage in GHG savings of electric vehicles both in the production and in the use phase. The expansion of renewable energies is therefore also the central lever for climate protection in the transport sector.

Overall, all modeled scenarios show significant GHG reduction potentials through the electrification of road freight transport. Since BEVs dominate in all scenarios, the availability of charging infrastructure is the key prerequisite for realizing the savings potentials in the comparison of the technology mixes.

5.5 Conclusions from market ramp-up modeling

The following conclusions can be drawn from the results of the market ramp-up scenarios:

- A CO_2-differentiation of the truck toll results in a strong economic incentive for emission-free drives, from which BEV, FCEV and O-BEV equally benefit. If the scope for ambition of the Eurovignette-Directive is exhausted, i.e. both a reduction from the infrastructure charge and an additional CO_2 component to account for external costs amounting to 200 €/t CO_2, zero-emission vehicles achieve robust cost advantages over conventional diesel trucks.

- BEVs dominate the heavy-duty vehicle market in perspective in all scenarios and technology pathways and across all size classes. A technology mix with FCEV or O-BEV results for the heaviest vehicle class, tractor-trailers, depending on the availability of energy infrastructures and the ratio of energy prices. In both mix scenarios, additional diesel trucks can be substituted, but substantial market share is gained predominantly through BEV substitution.

- The market ramp-up of BEVs is essentially determined by limited ranges or the availability of recharging options at high-power charging points. The price at public charging stations also influences the ramp-up and has a particular impact on the market share of BEVs among zero-emission drive systems. In order to achieve the German government's target of one-third electric driving share, a broad-scale and well-performing charging infrastructure for BEVs must be available between 2030 and 2035.

- The market ramp-up of FCEVs depends crucially on the achievable price of green hydrogen at refueling stations. The total cost of ownership of BEVs is less sensitive to the energy price due to their higher efficiency. In the modeling, a hydrogen price of €5.70/kg_{H2} in 2030 causes a ramp-up of FCEVs to 14% market share (and 33% in 2035) only in combination with high charging prices of 43 ct/kWh at megawatt charging points. For a higher price of €7.20/kg_{H2}, no FCEVs enter the modeled market.
- The market ramp-up of O-BEVs is determined by the availability of the energy infrastructure, similar to the situation for BEVs. Economically, O-BEVs have advantages over diesel trucks and, especially in combination with high charging prices, also over BEVs. However, the application possibilities are limited by the share of electrified route kilometers due to the limited battery storage in the vehicle. With an electrified core network in Germany (ca. 4,000 km), around one-third of the mileage of tractor-trailers is covered by electricity from the overhead catenary system.
- The availability of electric trucks is assumed to be a flanking factor in the market ramp-up modeling. The central incentive on the supply side is the CO_2 emission standards for heavy-duty vehicles. In all scenarios that achieve fleet electrification in line with the federal climate protection targets, the new registration shares exceed the EU's newly proposed fleet target values.
- Significant reductions in GHG emissions can be achieved in all scenarios for the electrification of heavy-duty vehicle fleets. In terms of road freight's share of total transport GHG emissions, a gap remains with the Federal Climate Protection Act in all scenarios, which can be closed from 2030 onwards depending on the scenario. The most important levers for reducing GHG emissions in road freight transport are the rapid expansion of charging infrastructure and an ambitious CO_2 differentiation in truck tolls.

6 Assessment of energy infrastructure demands

The market ramp-up scenarios show robust market potential for near-term electrification of new heavy-duty vehicle fleets. At the same time, the urgency of a rapid market ramp-up of electric powertrains to reduce GHG emissions from road freight transport becomes clear. In addition to a sufficient supply of vehicles, the availability of alternative energy infrastructures to supply electric vehicles is crucial for the success and speed of the transition to electric drives.

So far, there are hardly any demand estimates for charging infrastructures and possibly hydrogen refueling stations or overhead catenary systems for fully electrified road freight transport. Previous studies focus on demand estimates up to the year 2030 (ICCT 2022c, Fraunhofer ISI 2020a, ACEA 2020). The stock development in the modeled scenarios suggests that electric drives could already dominate road freight transport in the following years and require sufficient power supply beyond the needs of the year 2030. In case studies, the National Centre for Charging Infrastructure quantifies the potential power requirements at rest stops for trucks (NOW 2022a). The authors point out that grid operators have not yet considered the foreseeable power demand of trucks. According to the Federal Government's Master Plan for Charging Infrastructure II, a long-term and site-specific demand assessment should be carried out by the end of 2022 and made available to investors and grid operators (BMDV 2022). However, an overview of activities in November 2022 only shows data sources up to the year 2030 (NOW 2022b).

The aim of this chapter is therefore to estimate requirements for energy infrastructures up to the year 2045 on the basis of the modeled technology pathways and to make them publicly available. Since almost no public energy infrastructure for electric heavy-duty vehicles exists to date, the estimation is strongly driven by assumptions, as in the previously mentioned studies. In Sect. 4.5 and 4.8 the methodology used to distribute the modeled final energy demand among charging point types (operational vs. public, slow vs. fast charging) and, in a second step, regional transport demands is explained.

The demand estimates focus on the main scenarios of the respective technology pathways. For a technology mix of BEVs and FCEVs, the scenario "rech2035-lowH2" is chosen, in which a market for FCEVs is established due to favorable hydrogen prices. For the joint ramp-up of BEVs and O-BEVs, a demand-driven development of both energy infrastructures by 2035 is assumed ("BEV+O-BEV: rech&oc2035"). For the BEV scenarios, the three scenarios "recharge2030", "recharge2035" and "recharge2040" are used due to the large influence of charging infrastructure availability on the market ramp-up.

6.1 Final energy demand

The final energy demand is calculated from the energy consumption of the heavy-duty vehicle fleets in the modeled user profiles. The bottom-up determined energy demand is calibrated to the real final energy demand using data from AG Energiebilanzen[47] . The methodology for distributing the energy amounts to different charging point types is described in detail in Sect. 4.5.2.

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[47] AGEB - AG Energiebilanzen (2023). Energy Balance Sheet of the Federal Republic of Germany, https://ag-energiebilanzen.de/daten-und-fakten/bilanzen-1990-bis-2030/.

6.1.1 BEV scenarios

Electrification of commercial vehicle fleets reduces the annual final energy consumption of road freight transport from 172 TWh in 2020 to 112 TWh in 2045 (Figure 6-1). In the same period, an increase in road freight transport performance from 487 to 656 ton kilometers is assumed. The reason for the energy savings is the higher efficiency of the battery-electric drive compared to conventional trucks with diesel engines (cf. Sect. 4.3).

Electrification will increase the demand for electricity in road freight transport from almost zero at present to 76 TWh in 2035 and, in perspective, to 110 TWh if there is a complete switch to battery-electric drives. This corresponds to around 22% of Germany's total electricity demand in 2021 (AGEB). The study *Climate Neutral Germany 2045* projects a final energy demand of 231 TWh for the entire transport sector in 2045, with hydrogen and power-to-liquid fuels accounting for around a quarter of this demand (Prognos; Oeko-Institut; Wuppertal Institut 2021). The study assumes a lower increase in freight transport demand, as fewer fossil goods need to be transported, and assumes a declining transport performance of passenger cars resulting from a strong shift to climate-friendly modes of transport.

In addition to the total demand for (renewable) electricity, the following questions arise for the development of the energy infrastructure: What proportion of the electricity volume is required at publicly accessible charging points? And what charging power should be provided at the charging points to cover the current user profiles of transport vehicles as completely as possible? Since the development of charging infrastructure as well as the electrification of heavy-duty vehicle fleets as a whole is still in its infancy, only assumptions can be made about the future use of different charging types.

In the modeling, we estimate the usage shares of the different charging types based on a trip chain analysis of the survey *Motor Vehicles in Germany 2010* (cf. Sect. 4.5.2). We assume that the use of the charging types is as efficient as possible both economically and in terms of time. For the year 2035, this results in Figure 6-61 results in the following distribution:

- **Depot charging system (DCS):** The most favorable charging option is likely to be at the depot or at the transport companies themselves. If possible, all vehicles fully charge the battery at the depot at the beginning of each trip chain. In this idealized case, around 55 % of the electricity demand can be met via DCS charging points at moderate charging powers of up to 150 kW. The prerequisite for this is correspondingly long charging time of 6-8 hours, predominantly at night-times.

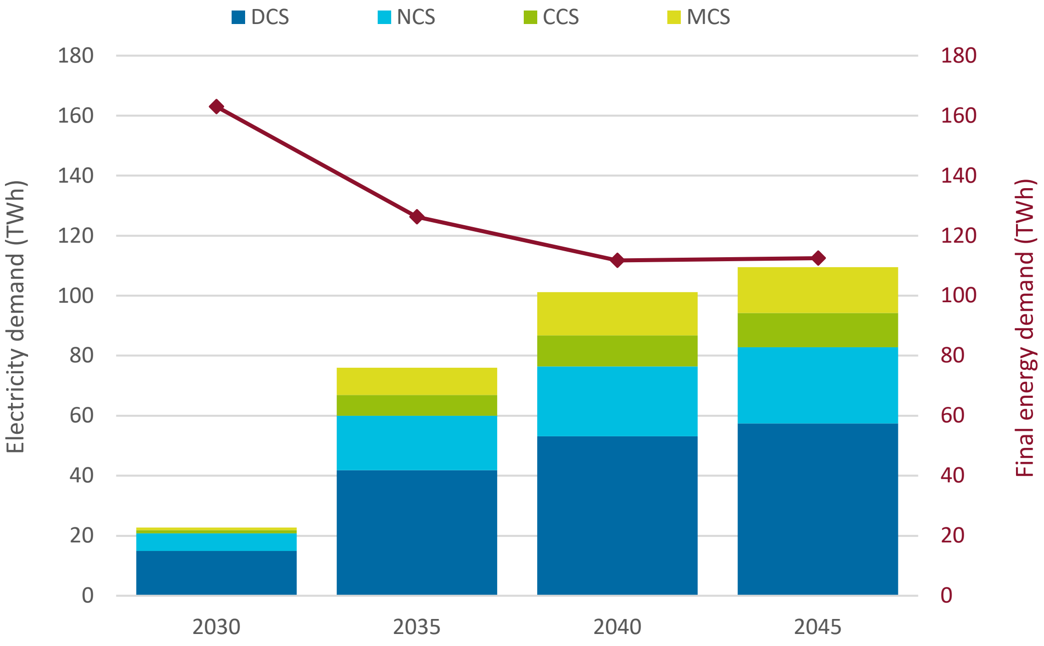
- **Night Charging System (NCS):** For multi-day driving chains, it is not ensured that the vehicles can return to the depot for recharging. We assume that the battery storage is nevertheless fully charged slowly once per operating day at moderate powers of up to 150 kW and that more expensive charging options with higher charging powers are only used for recharging if necessary. For slow recharging of the battery for chains of trips lasting several days, publicly accessible NCS charging points at parking areas are used. In this case, the electricity share at NCS charging points corresponds to about 24%. Accordingly, under the set assumptions for NCS and DCS, there is a potential for charging operations at charging powers of up to 150 kW totaling just under 80 % of the total electricity demand.

- **Combined Charging System (CCS):** For daily driving distances beyond the battery ranges of the trucks, the battery storage must be recharged at fast charging points. The CCS standard allows a charging power of 350 kW. If vehicles use this option and reach their daily destination with a single recharge at a CCS charging point, CCS charging power accounts for 9 % of total electricity demand.

- **Megawatt charging system (MCS):** MCS charging points with a peak charging power of 1000 kW are used when a single recharging stop at a CCS charging point is not sufficient to meet the daily mileage. Under these assumptions, the electricity share of MCS charging points is around 12 %.

Overall, under the assumptions made, just under 80 % of the electricity demand can be covered by charging the battery storage once per operating day. The remaining electricity must be recharged at fast charging points (CCS or MCS) during a recharging stop, if possible within the rest and driving pause.

Figure 6-1: Final energy demand in road freight transport in the "BEV" scenario "recharge2035" and estimation of a distribution among charging types



DCS: Depot Charging System, NCS: Night Charging System, CCS: Combined Charging System, MCS: Megawatt Charging System

Including 11 % charging losses at charging stations and 18 % energy losses at overhead line systems

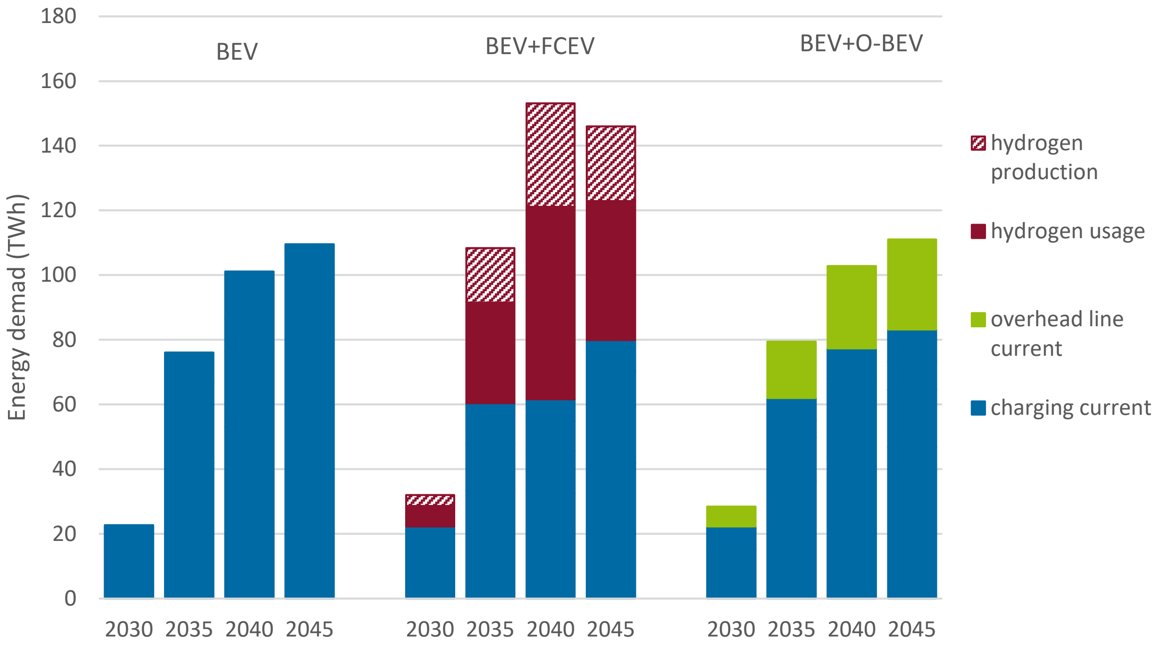
Source: Own calculations (including charging losses between charging station and vehicle).

The estimation of the distribution among charging types is based on simplifying assumptions. In practice, some shifts in usage patterns are conceivable. For example, charging times of 6-8 hours are generally not feasible for vehicles in multi-shift operation. However, the consequences are difficult to assess from today's perspective. Some of the companies will probably predominantly use fast charging points, while others may allow longer stopover times in operation due to the economic incentive. It is also conceivable that routes lasting several days could be organized entirely via private charging points at transport companies. For example, there are initiatives to open up commercial spaces to third parties to provide additional parking and, in the future, charging locations. On the other hand, high demand for public NCS already arises from transit traffic. Therefore, the estimate should not be interpreted as conclusive or complete; it can only provide guidance on how the projected battery ranges of vehicles and the required daily mileage are related and what recharging needs result.

6.1.2 Technology Mixes

For the comparison of the technology mix scenarios Figure 6-2 shows the development of energy demand in the scenarios "BEV: recharge2035", "BEV+FCEV: rech2035-lowH2" and "BEV+O-BEV: rech&oc2035":

Figure 6-2: Comparison of energy demand in road freight transport in the technology mix scenarios



Assumption: Efficiency for hydrogen supply from electricity (electrolysis and conversion): 65 %.

Including 11 % charging losses at charging stations and 18 % energy losses at overhead line systems

Source: Own calculations

- **BEV+FCEV:** If FCEVs complement the e-truck market due to favorable hydrogen prices, the demand for charging electricity is reduced. In the scenario considered, electricity demand at stationary charging points decreases by 20% in 2030 and by 40% in 2040 (with 36% FCEVs in the fleet). At the same time, due to the lower efficiency of the FCEV drive, the energy demand increases by 20% due to the use of hydrogen, or by about 40% if the electricity demand for hydrogen production is taken into account. In this scenario, hydrogen demand increases from 30 TWh in 2030 to nearly 60 TWh in 2045. By comparison, the annual hydrogen demand for current applications in the chemical industry is about 55 TWh (BMWi 2020). In addition, there are further requirements in the course of climate-friendly transformations in the steel industry and as a supplement to renewable energies in the energy sector, amounting to approx. 226 TWh in 2045 (Prognos; Oeko-Institut; Wuppertal Institut 2021). A demand for hydrogen in transport would thus be in direct competition with industrial applications, for which there are no technical alternatives to date. The German government's National Hydrogen Strategy envisages the production of 28 TWh of green hydrogen in Germany by 2035. (BMWi 2020). Consequently, demand for hydrogen in the transport sector would have to be met by imports.

- **BEV+O-BEV:** A combination of BEV and O-BEV also reduces the demand for stationary charging electricity. In 2030, the scenario results in a reduction of 18 % and in 2040 in a reduction of 24 %. Overall, the electricity demand increases slightly by 2-4 %. The reason for this is slightly increased energy consumption, which occurs with O-BEVs due to the additional flow resistance when the pantograph is extended and higher energy losses for energy supply at the overhead line.

Both technologies, FCEVs and O-BEVs, can therefore substantially reduce the need for stationary charging infrastructure. Nevertheless, in all scenarios - in line with the dominance of BEVs in the modeled market ramp-ups - at least half of the final energy demand is provided at stationary charging points.

6.2 Total energy infrastructure requirements

The demand for charging infrastructure and H_2-refueling stations is calculated from the final energy consumption and given performances of the energy infrastructures. We use individual charging points as the accounting variable and the number of H_2-dispenser as the counterpart. As described in Sect. 4.8, energy demands are apportioned regionally based on traffic volumes. In this section, the regional demands are summed to create a total demand. The demand for overhead line infrastructure is taken directly from the predecessor project StratON (Oeko-Institut; HHN; Fraunhofer IAO; ITP 2020).

6.2.1 BEV scenarios

In a purely battery-electric scenario with area-wide and demand-driven charging infrastructure from 2035 ("BEV: recharge2035"), there is an enormous need for development and expansion over the next 10 years. The following relationships emerge for the various charging point types:

- **Depot Charging System (DCS):** At least 90,000 depot charging points will be needed in operations by 2035. This number likely represents a lower bound for charging capacities of 150 kW and a load factor of 1.5 trucks per charging point. In many operations, lower charging capacities will be practical, especially for vehicles with smaller battery systems. The number of charging points required is correspondingly higher. If one depot charging point is set up for each truck, the requirement rises to 150,000 depot charging points for the tractor-trailer segment alone.

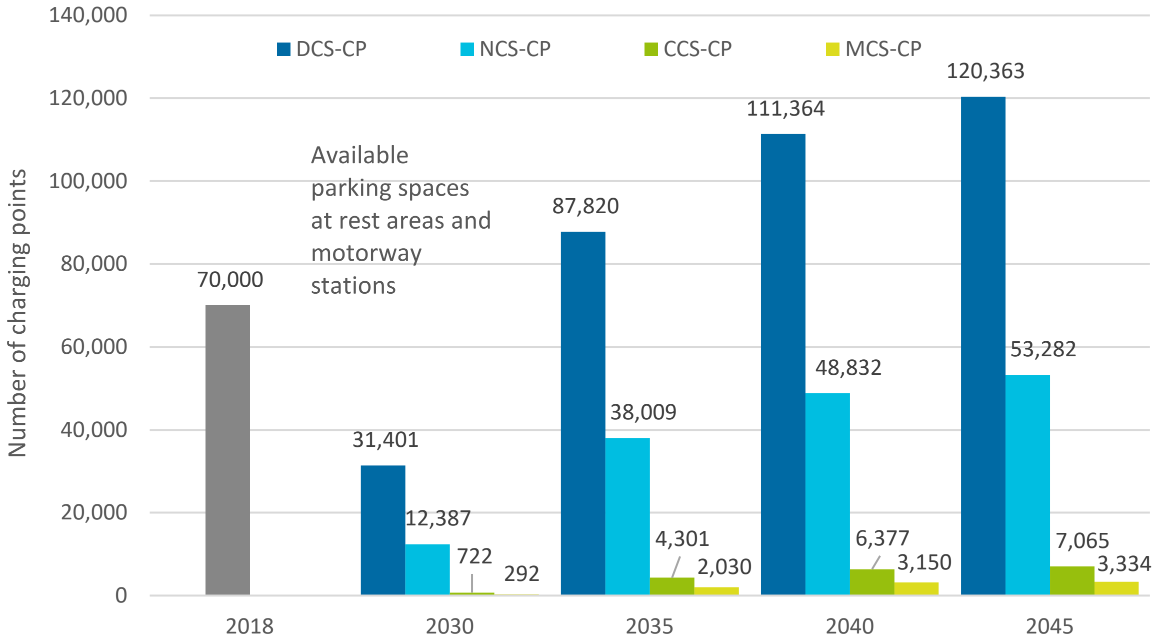
- **Night Charging System (NCS) and parking spaces:** Our estimates indicate a need for nearly 40,000 NCS charging points by 2035 and, prospectively, about 55,000 NCS CPs by 2045. A 2018 study by the Federal Highway Research Institute (BASt) puts the number of available parking spaces at rest areas and motorway stations at about 70,000; of these, about 40,000 spaces are at managed rest areas and motorway stations (BASt 2018). In purely mathematical terms, the parking spaces would therefore be sufficient for the demand for NCS charging points. However, the BASt study points out that an average of about 23,500 additional trucks are parked "wildly" at night, for which parking spaces are already not available. The parking space capacity bottlenecks could be exacerbated by required nighttime loading demands and should be addressed through reservation and booking systems.

- **Combined charging system (CCS):** For CCS charging points, there is a need for around 4,300 charging points by 2035. In the modeling, CCS is used almost exclusively by BEV200s with moderate mileages of up to around 300 km. High daily mileages require large battery storage and additional recharging at MCS charging points. The establishment of CCS charging points is therefore particularly suitable for regional transports. For example, loading and unloading ramps could be equipped with CCS charging points to enable efficient recharging during planned idle times.

- **Megawatt Charging System (MCS):** The new MCS charging standard will be required at around 2,000 public charging points by 2035. High-power charging will be required primarily on highways for recharging within the legally prescribed driving breaks (45 min after 4.5 hours of driving). Since only prototypes for MCS charging points exist so far (cf. Schaal 2022a, Schaal 2022b) and time spans of several years for planning, approval and implementation of the network connections are typical, the required construction of an average of 200 MCS charging points per year from 2025 to 2035 is to be assessed as critical.

The development of the charging infrastructure required to enable the use of BEVs in road freight transport is proving to be challenging, primarily due to the time pressure of fleet electrification. This applies in particular to the need for MCS charging points, which account for only a small share of the electricity demand, but whose availability is essential for the possible use of BEVs in high-emission long-distance transport.

Figure 6-3: **Demand for charging points (CP) in road freight transport according to charging types in the "BEV" "recharge2035" scenario**



Assumptions: Rated powers: DCS - 150 kW, NCS - 150 kW, CCS - 350 kW, MCS - 1000 kW (of which 85% average power).

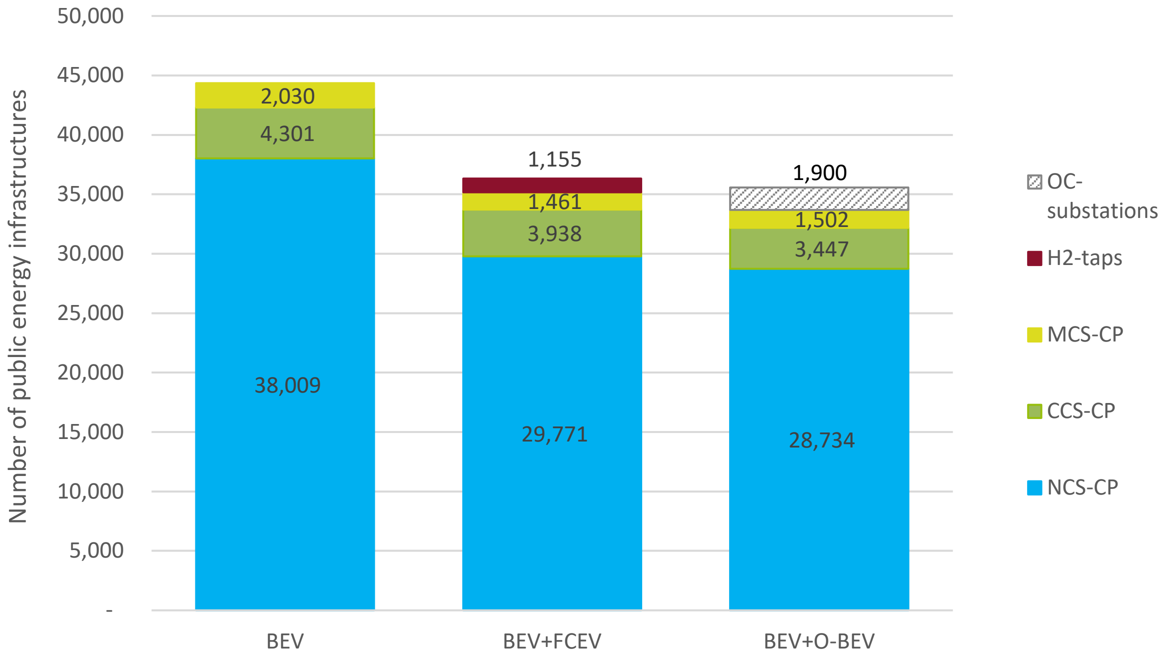
Source: Own calculations and BASt 2018

6.2.2 Technology Mixes

For the comparison of the technology mixes, we focus on the needs for publicly accessible charging infrastructure in 2035. The savings for depot charging points are similar in magnitude to those for NCS charging points. The comparison in Figure 6-4 shows:

- **BEV+FCEV:** The deployment of FCEV with ranges expected to be 1000 km in 2030 targets long-distance transport. It saves 22% of NCS and 28% of MCS charging points compared to the BEV-only scenario. The saving of about 570 MCS charging points is matched by a need for H_2 charging stations with a total of 1,155 taps.
- **BEV+O-BEV:** A suitable comparison with discrete stationary charging points is hardly possible for the line-by-line construction of overhead line infrastructure, so for classification purposes we show the demand for substations, which are erected approximately every 2 km to supply power to the overhead line system. The average power per substation is 2.8 MW, which is higher than the rated power of an MCS charging point (cf. Sect. 6.3.3). In sum, the deployment of O-BEV saves stationary charging points to a similar extent as FCEV, to the extent of 20 to 25 % compared to the BEV-only scenario. In return, about 1,900 substations are required to build an overhead line core network on the busiest highways in Germany.

Figure 6-4: Demand for public charging points, H_2 dispenser, and overhead line substations in 2035 in the technology mix scenarios (all HDV).



"BEV: recharge2035", "BEV+FCEV: rech2035-lowH2", and "BEV+O-BEV: rech&oc2035".

Charging points (CP): DCS: depot charging system, NCS: night charging system, CCS: combined charging system, MCS: megawatt charging system / OC-substations: substations for overhead line infrastructure, H_2-taps: dispenser at hydrogen refueling stations.

Source: Own calculations

Compared to the BEV-only scenario, the technology mix scenarios show significant savings potential for stationary charging points, which could cushion the challenging construction of megawatt charging points in particular. However, the additional construction of hydrogen refueling stations or overhead line systems also proves to be challenging. For example, there are currently no hydrogen refueling infrastructures on the scale required, and the use of overhead contact line systems has so far been limited to a few route kilometers and low vehicle utilization (cf. sections 2.2, 6.3.2 and 6.3.3). As was already made clear in the market ramp-up scenarios, a market uptake of BEVs and the associated need for stationary charging infrastructure can be assumed to be almost certain. However, there is still a high degree of uncertainty as to its required characteristics and design. In summary, it can be stated that critical challenges for the urgent development of energy infrastructures exist for all technology pathways.

6.2.3 Comparison with AFIR requirements

At the EU level, binding minimum targets for the development of alternative energy infrastructures are expected to come into force this year to ensure unrestricted transportation with alternative drives within the EU (cf. Sect. 3.3). For heavy-duty vehicles, the regulation targets area coverage, while for passenger cars and light-duty vehicles, additional fleet-specific targets come into play. Performance specifications for charging locations are prescribed at defined maximum distances on the TEN-T network. In addition, performance specifications apply at urban nodes and at Safe and Secure Parking areas (cf. section 3.3). To a lesser extent, hydrogen refueling stations are also to be built.

In Table 6-1 minimum targets of the AFIR are compared with the requirements determined in the scenarios. If the targets are added up for each site, the minimum capacity to be installed at public charging sites in Germany by 2030 is around 1.1 GW. For hydrogen refueling stations, the targets envisage a total capacity of approx. 140 tons/day from 2030. In contrast to the original proposal of the EU Commission, the final version of the AFIR does not specify any target values for the year 2035. However, the development of demand shows a strong increase in electricity and hydrogen demand in road freight transport, especially in the period from 2030 to 2035.

Compared to the AFIR proposal, the scenarios result in the following needs:

- **BEV**: Already in 2030, the demand for public charging capacity exceeds the minimum requirements of the AFIR by a factor of two. The discrepancy grows to a factor of eight in 2035. An estimate of EU-wide charging infrastructure needs by ICCT also calculates higher needs for 2030 compared to the EU Commission's proposal at that time, which for the year 2030 is in a similar order of magnitude as the final version of the law (ICCT 2022c).

- **BEV + FCEV:** Although fuel cell trucks reduce the need for public charging infrastructure, the modeled requirements still significantly exceed the minimum requirements formulated in the AFIR even in the mix scenario. Hydrogen demand, which is calculated to be about 600 tons per day in 2030, is about a factor of four higher than the AFIR's requirements. The minimum targets for hydrogen refueling stations are probably more conservative, since there is still greater uncertainty regarding the market development of FCEVs than regarding BEVs.

- **BEV + O-BEV:** A build-out of overhead line infrastructure also reduces the need for public charging infrastructure. However, the overhead line core network requires about another 80% to 100% of the capacity of the public charging infrastructure in addition to enable the stock of O-BEVs to drive simultaneously (without recharging the battery) on the overhead line.

In total, fleet electrification in Germany requires a build-up of public energy infrastructure that is significantly higher than the targets set out in the AFIR. For the revision of the AFIR in 2026, the ambition level for the targets from 2030 should be significantly increased. As already discussed in connection with the CO_2 emission standards for heavy-duty vehicles in Sect. 5.5 the national climate protection legislation and targets necessitate a commitment that goes well beyond the minimum EU targets.

Table 6-1: Estimated demands of public energy infrastructure, fleet share of electric tractor-trailers (TT), and AFIR targets.

	Unit	2030	2035	2040	2045
AFIR					
Total power of charging points[1]	GW	1.1	1.1[2]	1.1[2]	1.1[2]
Total capacity of hydrogen	t/day	140	140[2]	140[2]	140[2]
BEV: recharge2035					
Share of BEVs in stock (TT)	%	17	63	92	100
Total power of charging points	GW	2.4	9.2	12.7	13.8
BEV+FCEV: rech2035-lowH2					
Share of BEVs in stock (TT)	%	17	51	57	70
Total power of charging points	GW	2.4	7.3	7.7	10.0
Share of FCEVs in stock (TT)	%	3	16	36	30
Total capacity of hydrogen	t/day	607	2,994	5,714	4,129
BEV+O-BEV: rech&oc2035					
Share of BEVs in stock (TT)	%	15	47	63	68
Total power of charging points	GW	2.2	7.0	8.9	9.7
Share of O-BEV in stock (TT)	%	6	20	29	32
Total power of OC system[3]	GW	1.7	5.5	8.5	9.7

[1] Assumption: 100 *Safe and Secure Parking Areas* by 2030 (estimate based on. ICCT 2022c)

[2] No further targets have been formulated for the years after 2030. The EU Commission's original proposal included targets up to 2035.

[3] Assumption: 120 kW per vehicle with simultaneous use of overhead catenary (OC) system (without additional 150 kW for recharging).

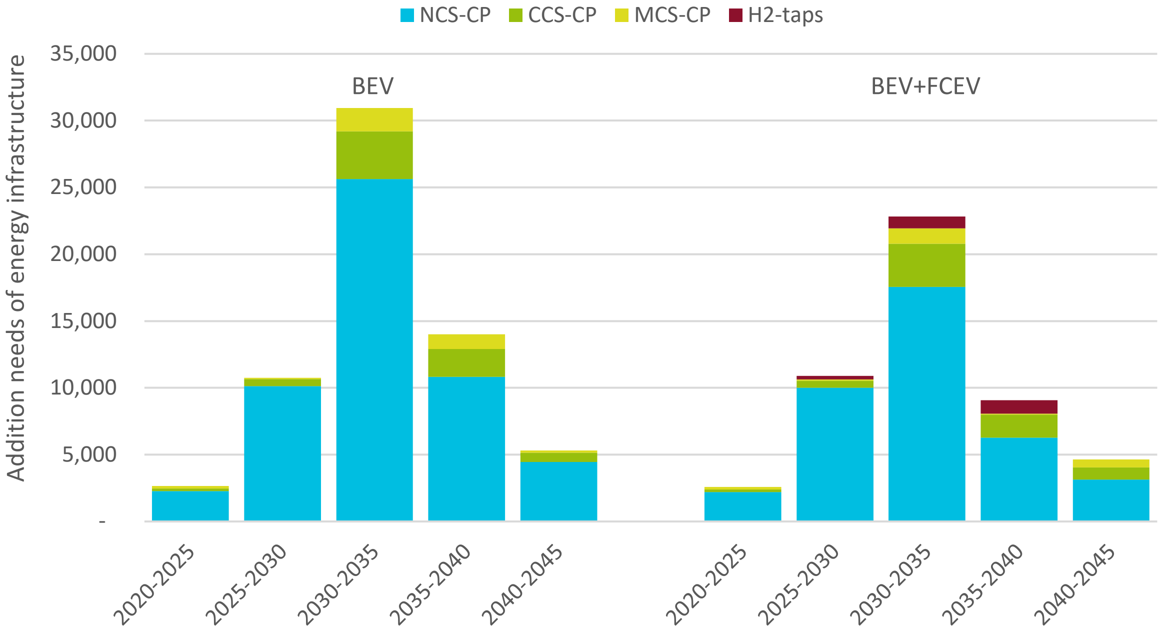
Source: Own calculations and AFIR 2023

6.2.4 Investment requirements

Building new energy infrastructure to power a heavy-duty electric transport system requires investment. Figure 6-5 shows the addition of charging points and hydrogen dispensers as would be required according to the needs assessment in the modeled scenarios. The bulk of the additions occur in the period from 2030 to 2035. In terms of numbers, the needs for overnight public charging points (NCS) stand out, but the addition of megawatt charging points and hydrogen dispensers requires more investment per unit (cf. Sect. 6.3). The technology mix of BEVs and O-BEVs is not additionally shown here. The requirements for charging infrastructure are, as described in Sect. 6.2.2 described, are of the same order of magnitude as in the technology mix scenario of BEV and FCEV.

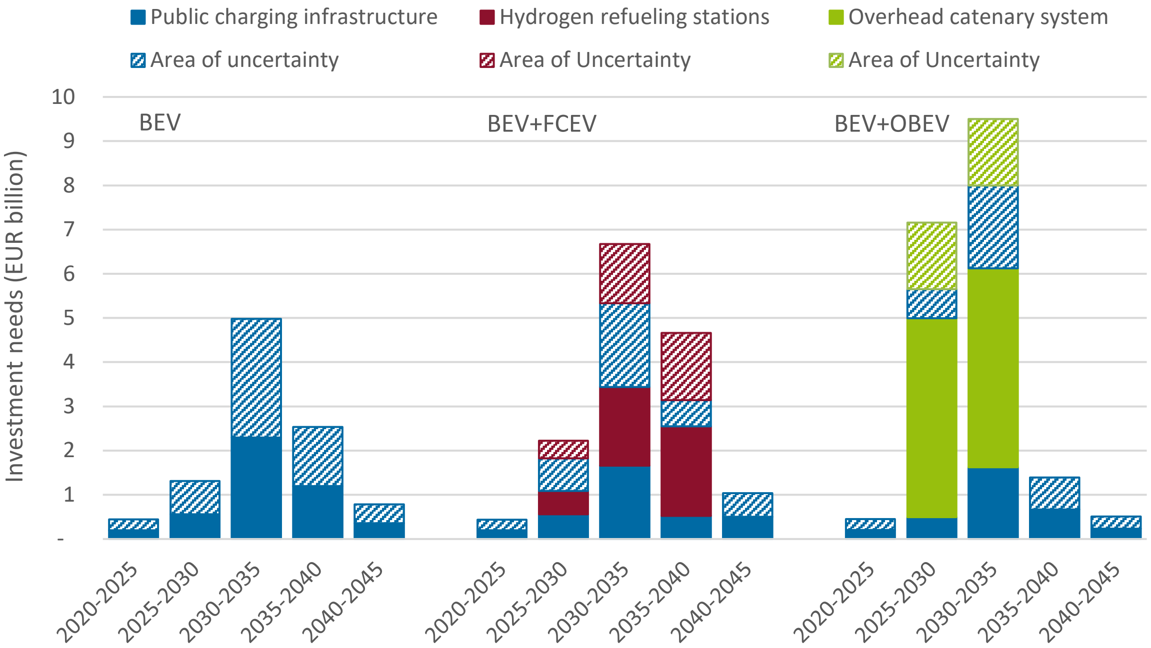
The deployment of the overhead catenary core network is assumed to be 1,900 km in the period 2025 to 2030 and an additional 1,900 km in the period 2030 to 2035.

Figure 6-5: **Addition of charging points and H_2 dispenser in the scenarios "BEV: recharge2035" and "BEV+FCEV: rech35-lowH2".**



Source: Own calculations

Figure 6-6: **Investment requirements for public energy infrastructures in comparison of the technology mixes**



Source: Own calculations based on Oeko-Institut; EWI; FCN 2022, Fraunhofer ISI 2020b and Oeko-Institut 2018

From the capital costs of the energy infrastructures listed in section 4.6. the investment needs are calculated and presented in Figure 6-6. The shaded area indicates an uncertainty range between the lower and upper cost ranges shown. According to this, the purely battery-electric technology pathway is associated with the lowest investment requirements. In total, approximately €5 billion to €10 billion will be required by 2045. In the technology mix of BEVs and FCEVs, the savings in charging infrastructure are more than offset by the additional high investments in refueling infrastructure for hydrogen. In total, €8 to 15 billion in investments will be required.

According to the demand estimate, the highest investment requirement is for the joint development of charging infrastructure and overhead catenary systems, with a total of €20 billion to €34 billion. This is partly due to the fact that our demand estimate for charging infrastructure and hydrogen refueling stations is based on modeled demand, while the expansion stages of the overhead contact line network are included as an input variable in the modeling. Temporary oversizing is therefore possible and also likely in actual implementation.

Nevertheless, of the three technology options, the construction of overhead contact line systems on highways is likely to involve the highest initial investment. Nevertheless, financing of the energy infrastructures is ensured in all three technology pathways by including an infrastructure charge in the total costs (cf. Sect. 4.6).

So far, the costs of energy infrastructures have not taken into account the upstream chains of distribution, i.e. transport infrastructures for hydrogen or potential upgrades of the power grid for charging locations or overhead line systems. The quantity structures of energy infrastructures developed via the scenarios should help to consider future electricity and hydrogen demands in road freight transport more closely in energy-economic planning.

6.3 Regional demands along the highways

For the design and dimensioning of charging locations, hydrogen refueling stations or overhead catenary systems, this section shows the requirements for public energy infrastructures weighted by regional traffic volumes. For this purpose, in a first step, a location grid was created along the federal highway network, which is based on AFIR's distance specifications for the year 2030. In a second step, the modeled final energy demand is allocated to the local transport demand of the sites as described in Section 4.8. The number of charging points and hydrogen dispensers is derived from the average peak local transport demand.

The locations outlined in this section are not to be understood as site recommendations for practical implementation. Other criteria, such as space availability, ownership and grid connection options, are decisive for this selection. Rather, the goal is to provide an overview of the quantity requirements for charging points or H_2 dispenser depending on traffic demand, as well as statements about the power to be installed, electricity or hydrogen requirements, and the potential utilization of the infrastructures. To do this, the sites are divided into five size categories based on traffic volume. The focus is on demand in 2035, since by that time more than 50% of the heavy-duty vehicle stock in the scenarios will already be electrified.

6.3.1 Charging stations

For a grid of charging locations on the federal highway network, we assume a distance of 60 km[48] and add charging stations at urban intersections. Depending on traffic volume, the sites are divided into five size categories. In Figure 6-7 one marker stands for two charging hubs, i.e., one charging hub per direction of travel. This results in a total of 380 locations across both directions of travel. The distribution of the loading hubs across the location categories is shown in Table 6-2. Most locations belong to the largest location category with the highest traffic volume, followed by the two smallest size categories.

The daily profile of the local traffic volume is used to calculate the peak power per site and thus determine the number of charging points required. The procedure is described in detail in Sect. 4.8. For the charging point types, we determine the following requirements for the year 2035:

- **MCS charging points:** The need for MCS charging points varies between 2 and 10 charging points per location category. The estimate agrees well with results in T&E 2021 and Fraunhofer ISI 2020a although the approaches in the studies differ in some cases. Although local traffic volumes are used consistently to estimate local charging point requirements, the accounting variables differ. T&E 2021 vary the state of charge of arriving trucks at charging locations using a Monte Carlo simulation and obtain a demand of 4 to 14 MCS charging points per charging station depending on local traffic demand. In this study, as described in Fraunhofer ISI 2020a and ICCT 2022c, the total final energy demand is apportioned over the local traffic volume. The number of charging points required per charging station is determined in Fraunhofer ISI 2020a via a queuing model, while this study uses the average peak load per site for sizing. The quantity frameworks agree well if the boundary conditions in Fraunhofer ISI 2020a of 15% BEV in the stock and an assumed share of 50% MCS charging are converted to the boundary conditions of this study (more BEV, less high-power public charging).
- **NCS charging points:** For NCS, we calculate a demand of 24 to nearly 200 charging points per site. In order to relieve the large sites, it is recommended to distribute the NCS charging points to additional rest areas and motorway service stations. T&E 2021 indicates a slightly higher number of NCS charging points of about 40 to 220 charging points depending on traffic volume, although the quantity figure is not based on a demand estimate, but rather uses the data presented in BASt 2018 as the basis for derivation.

The need for CCS charging points is not shown here in connection with charging locations along the highway network because, as described in Sect. 6.2.1 the demand in the modeling is focused on regional traffic. For long-distance traffic, a recharging stop at a CCS charging point within the driving break is generally not sufficient. However, as a transition to the MCS standard, a timely development of CCS charging options along the highways makes sense.

Important benchmarks for the charging locations are summarized in Table 6-2. The rated power increases as traffic demand increases from 5 MW in Category 1 to 39 MW in Category 5. The high utilization of MCS charging points of 12 to 18 hours per day (at average power) indicates that energy or traffic demand is relatively evenly distributed throughout the day. In the exemplary daily load curve in sec. 4.8 there is a characteristic drop in traffic demand between 10 p.m. and 4 a.m., as well as during the peak demand periods around 7 a.m. and between 3 p.m. to 5 p.m. Accordingly, even at

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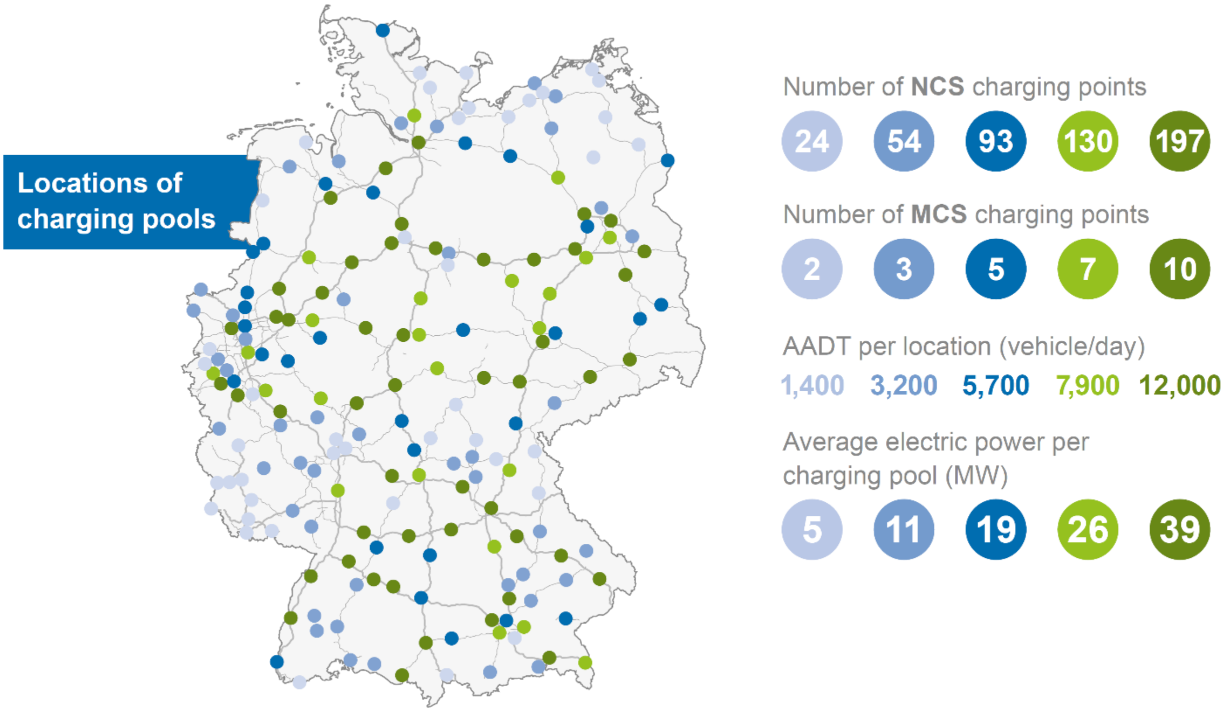
[48] More specifically, the AFIR provides for a maximum distance of 60 km between two charging locations on the TEN-T core network by 2030 and a maximum of 100 km on the TEN-T overall network.

the lower-traffic location categories on the highway network, the potential for economic utilization of the charging points appears to exist given sufficient market penetration of e-trucks.

If the high utilization of MCS charging points is realized in practice, this means that phases of simultaneous use of MCS and NCS charging points may occur. If traffic demand and recharging needs correlate (as implicitly assumed), possible overlaps in the use of NCS and MCS charging points occur during peak hours in the early morning. Therefore, the nominal capacity of the sites is shown in Table 6-2 cumulatively across the MCS and NCS charging points.

Figure 6-7: Derivation of size categories for charging hubs on highways in 2035 based on local traffic volumes ("BEV: recharge2035").



Source: Own calculations and Speth et al. 2022

Table 6-2: Average power per charging station in 5 size categories for the year 2035

Category	Unit	1	2	3	4	5
Number of locations for both directions		84	90	60	46	100
AADT per direction	Vehicle/ day	1,400	3,200	5,700	7,900	12,000
Average power consumption per site	MWh/day	54	122	214	298	452
Nominal power per site	MW	5	11	19	26	39
Utilization MCS-LP[1]	h/day	11.8	15.1	16.8	17.5	18.0

[1] Pure charging time at average power output (average power / rated power = 0.85), utilization NCS charging points: approx. 12 hours per day

Source: Own calculations

The charging pools are connected to the medium-voltage grid or, with considerable additional effort, to the high-voltage grid. For a grid connection to the high-voltage grid, the National Centre for Charging Infrastructure specifies a threshold of approx. 30 MVA [49](NOW 2022a). In this context, a surcharge for reactive power must be taken into account, for which the study specifies a power factor of 95 %. In addition, the power balance of the sites usually takes into account additional fast charging points for passenger cars, which require a further approx. 5 to 10 MW of power. In turn, the authors of NOW 2022a and T&E 2021 point to significant potential to reduce the required connected load of the sites via charging management. The potential in turn depends on the simultaneity and duration of the charging processes. Accordingly, the connected load to be determined in individual cases can vary from the values given in Table 6-2 but will potentially be in the order of magnitude given the above considerations.

As a result, a connection to the high-voltage grid will in all likelihood be necessary for category 5 and probably also 4 sites. If opposite locations are connected to the power grid together for both directions of travel, a connection to the medium-voltage grid will already no longer be sufficient for category 3 locations in 2035. By 2045, the demand for charging points will increase by about 1.5 times. A further densification of locations should be targeted from 2035 at the latest. If private charging options do not materialize to the extent assumed in this study, the demand for public high-performance charging hubs will increase and connection requirements to the high-voltage grid will become even more likely.

Implementation times for connecting charging pools to the high-voltage grid can be up to 10 years (NOW 2022a). Accordingly, early and targeted planning of truck charging infrastructure along the highway network is urgent. To enable widespread deployment of e-trucks by 2035, planning of connectivity options to the high-voltage grid along federal highways must begin promptly.

6.3.2 Hydrogen refueling stations

The estimation of the local demand for hydrogen and refueling infrastructures is carried out analogously to the procedure described for charging locations. The grid of locations along the highway network is smaller, based on the EU Commission's AFIR draft. The distance between two hydrogen filling stations is a maximum of 150 km[50] with densification at junctions. The total demand for hydrogen calculated from the market ramp-up modeling in the "BEV+FCEV" scenario "rech2035-lowH2" is allocated to the fictitious locations based on local traffic volumes and divided into 5 size categories for the locations (Figure 6-8). The quantities refer to the required number of hydrogen dispensers per refueling station.

As a result, depending on the traffic volume, refueling station capacities of 4 to 34 tons hydrogen per day are required to supply the fuel cell trucks used in the scenario (Table 6-3). The number of dispensers per fueling station varies with the size category from 2 to 12 H_2 dispensers to serve the local hydrogen demand during the peak day. In a study, Fraunhofer ISI determines a filling station demand in six size categories in perspective for the year 2050 with a similar hydrogen demand in the largest category of 30 tons hydrogen per day with 16 dispenser per refueling station (Fraunhofer

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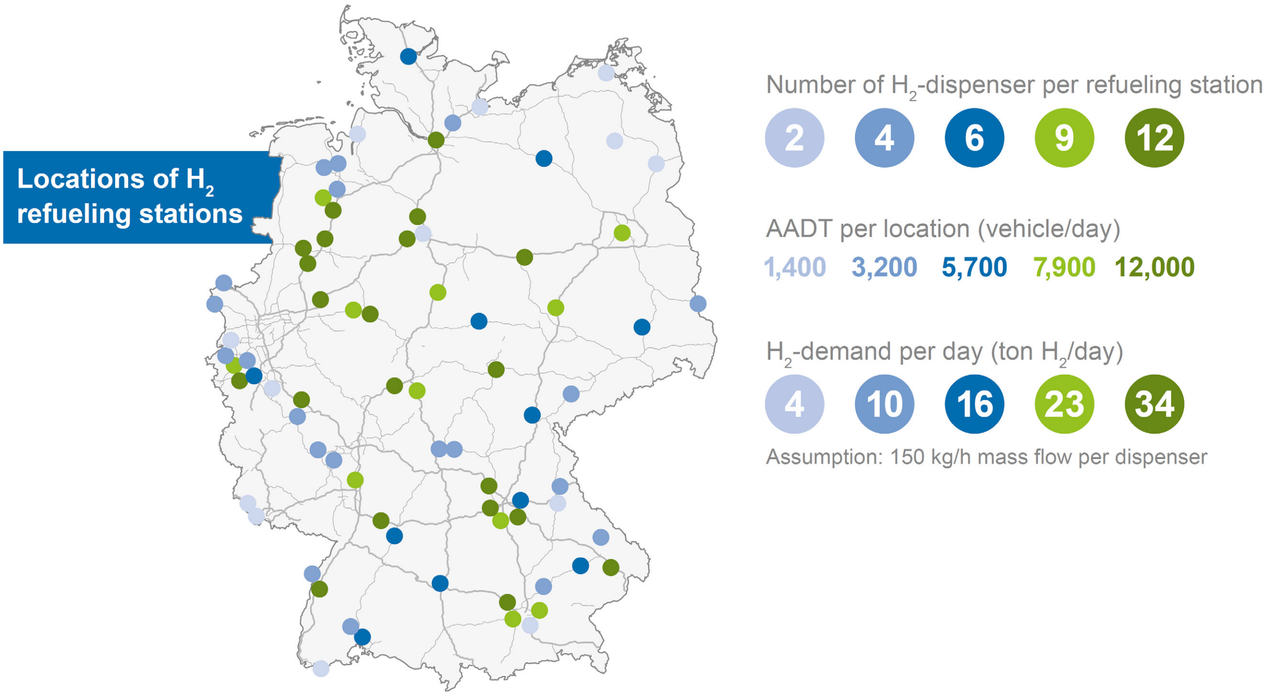
[49] The unit MVA ("mega volt ampere") is used for the apparent power of AC systems. In addition to the active power in MW ("megawatts"), the apparent power includes the reactive power for the buildup of electric or magnetic fields.

[50] The July 2023 final version of the AFIR specifies a minimum distance of only 200 km. The present needs assessment for hydrogen refueling stations had already been completed at that time.

ISI 2020b). For the use of hydrogen in heavy-duty transport, there is thus a considerable need to scale up existing hydrogen refueling infrastructures.

Figure 6-8: Derivation of size categories for H_2 refueling stations on highways in 2035 based on traffic volumes ("BEV+FCEV: rech35-lowH2").



Assumption: Delivery rate of hydrogen per dispenser: 150 kg/h

Source: Own calculations

Table 6-3: Average capacity per hydrogen refueling station in 5 size categories in year 2035

Category		1	2	3	4	5
Number of locations for both directions		36	44	22	24	44
AADT per direction	Vehicle/ day	1.400	3.200	5.700	7.900	12.000
H_2 capacity per site	t /day	4	10	16	23	34
H_2 volume per site (storage at 200 bar)	m^3	284	654	1.105	1.549	2.284
Utilization per dispenser[1]	h/day	12,7	15,4	17,0	17,6	18,2

[1] Assumed nominal capacity per tap: 150 kg/h

Source: Own calculations

According to the operator of the German hydrogen refueling station network H_2 Mobility, capacities of 0.5 tons hydrogen per day are available at the established hydrogen refueling stations in the "medium" category for passenger cars and light commercial vehicles (H2 MOBILITY 2021). For the supply of heavy commercial vehicles, "XXL" refueling stations with a capacity of 2.5 tons per day are calculated with 2 to 4 taps per refueling station. According to the estimates of this study, this would only be sufficient for an initial market phase of fuel cell trucks. If the hydrogen demand is distributed over more locations by a denser grid of the filling station network, the capacities can be reduced, but at least a scaling by one order of magnitude compared to current hydrogen refueling capacities will be necessary at busy corridors.

It is also unclear in which aggregate state the hydrogen is to be refueled. The storage of gaseous hydrogen at 350 bar already realized in fuel cell trucks allows ranges of about 400 km (Hyundai 2020). For use in long-distance transport, the pressure level will have to be increased to 700 bar (as in passenger cars) or liquefaction will be necessary. For both technologies, there is a need for development to realize the refueling volumes required in heavy-duty vehicles in short filling times[51] . In addition, there is the enormous space requirement resulting from the on-site storage of the hydrogen volumes. The volume of 34 tons of hydrogen at 200 bar storage pressure corresponds to 2,284 m^3. Fraunhofer ISI 2020b indicate a space requirement of 13,470 m^2 for a filling station of this size, which corresponds to almost two soccer fields.

However, as with the high-power charging stations, the potentially biggest challenge is the energy supply to the sites. Currently, the existing hydrogen refueling stations are supplied with gaseous hydrogen at a storage pressure of 200 to 500 bar via tank trucks (H2 MOBILITY 2021). Modern gas trailers can transport about 1 ton of hydrogen at a storage pressure of 500 bar (H2 MOBILITY 2021, CAM 2020). If the hydrogen is liquefied, about 4 metric tons can be transported by trailer (CAM 2020). If demand for hydrogen arises from (only) 16% of the trucks and tractor-trailers used in road freight transport by 2035, as in the scenario shown, a Category 3 hydrogen refueling station would have to be supplied by hydrogen trailers at least four times a day. As discussed in sec. 4.7 an onsite production of hydrogen at the filling station is hardly economically feasible. Supply via new or repurposed pipeline networks is possible in principle, but requires early planning. Due to the remaining uncertainties about a stable market development of fuel cell trucks, as discussed in connection with the market ramp-up scenarios (cf. Sect. 5.2), investments in distribution and refueling infrastructures for hydrogen filling stations are associated with high risks.

6.3.3 Overhead catenary systems

In the predecessor project StratON, an overhead line network was developed on the basis of traffic analyses, which covers about 4,000 km of the BAB network, with about 10 % of the route not electrified due to structural conditions (e.g. tunnels and bridges) (Figure 6-9). The power supply for the overhead contact line systems is provided in sections via substations, which are built at intervals of about 2 km (Oeko-Institut 2018, Boltze et al. 2021). Compared to high-power charging stations, the electricity in overhead line systems is thus distributed more broadly over the area. Analogous to the estimation of local demand for charging and refueling infrastructure, the total energy demand of overhead line systems is allocated to substations based on local traffic volumes. Since the construction of overhead line systems is limited to high traffic highway sections, the 1st category is omitted in the formation of the size categories.

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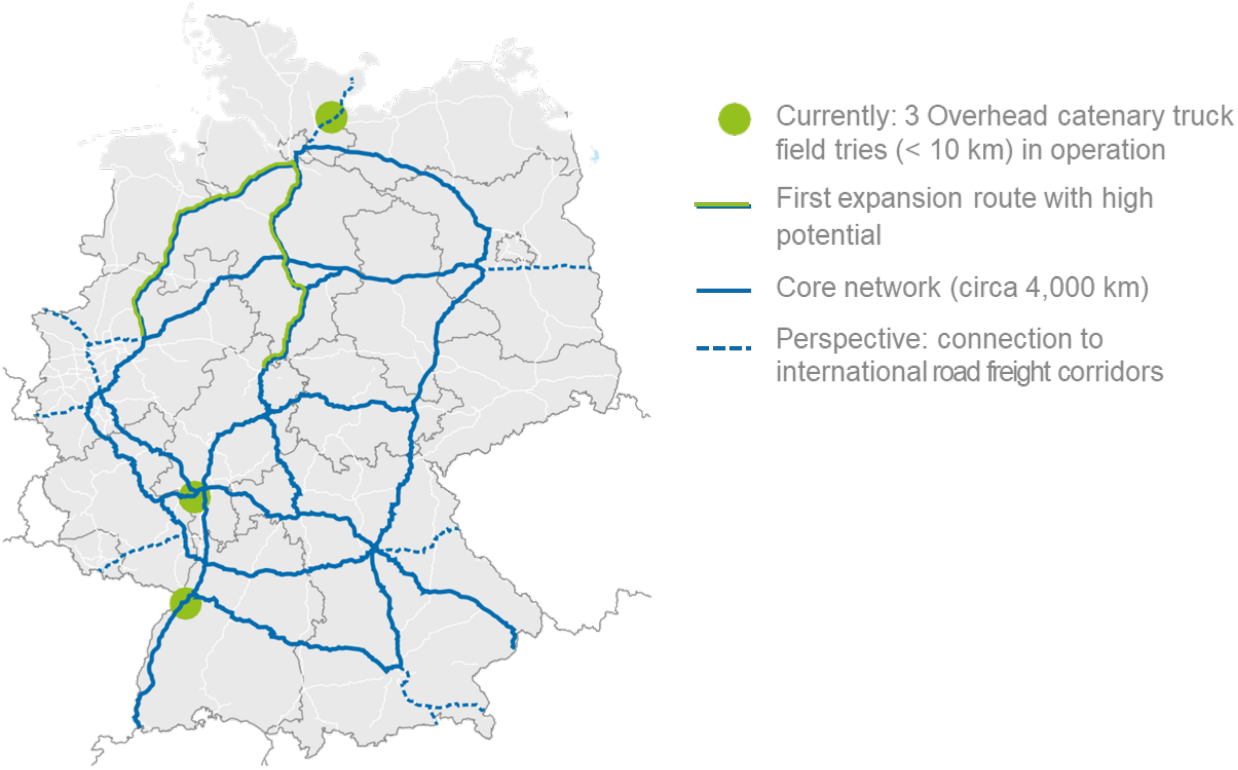
[51] The European "PRHYDE" project is developing refueling protocols for heavy-duty fuel cell commercial vehicles and recommendations for standardization.

Figure 6-9: **Overhead catenary core network on highly frequented highways from the StratON project.**



Source: Oeko-Institut; HHN; IAO; Intraplan 2020

Table 6-4: **Average power per overhead contact line section in 4 size categories in the year 2035 ("BEV+O-BEV:rech&oc2035").**

Category		2	3	4	5
Number of substations for both directions		578	385	295	642
AADT per direction	Vehicle/ day	3;200	5;700	7;900	12;000
Power per substation	MW	1.3	2.2	3.1	4:6

Assumptions: 1 substation per 2km for both directions, 120 kW power consumption per O-BEV in the existing system.

Source: Own calculations based on Oeko-Institut 2018 and Boltze et al. 2021

The estimation shows that a power of about 1.3 to 4.6 MW is required per substation (Table 6-4). The substations are connected to the power grid individually or, more likely, bundled via busbars. Depending on the bundling, a connection to the medium-voltage grid is possible or the accumulated power makes a connection to the high-voltage grid necessary. In purely mathematical terms, this would be necessary for the presented power demand in 2035 for a bundling of about 10 substations or of 5 substations if both directions of travel (cf. Section 6.3.1).

The energy supply for overhead contact line systems on highways is therefore also likely to be challenging and time-critical. In order for overhead catenary trucks to be able to cover a quarter of the mileage in heavy-duty traffic in 2035, planning for overhead line systems and network connections would have to begin promptly. The need for high-capacity charging hubs along the highways, which present themselves in all modeled scenarios, can result in synergies for parallel power supply of overhead line systems with regard to grid connections. A timely organization of connection options to the high-voltage grid along the highway network is central to the switch to electric heavy-duty transport.

6.4 Conclusions from the assessment of energy infrastructure needs

The following conclusions emerge from the assessment of energy infrastructure deamnds for electric heavy-duty vehicles:

- As a result of the more efficient operation of electric vehicle drives, final energy consumption in road freight transport is falling. The switch to a completely electricity-based energy supply will generate an annual electricity demand of 110 TWh for the operation of heavy-duty vehicles by 2045.
- If substantial market shares of FCEVs are realized due to a favorable supply of hydrogen refueling stations, 30 to 60 TWh of green hydrogen will be required annually in the future. In this scenario, the electricity demand for stationary charging points will decrease by about a quarter. An expansion of overhead catenary systems on highly frequented highways reduces the electricity demand for stationary charging points by about the same amount.
- Despite remaining uncertainties about the user demand of private charging points and interactions with other drive technologies, the modeled technology pathways indicate robust needs for public charging infrastructures for heavy-duty vehicles. The development of hydrogen refueling stations is associated with risks due to the higher dependence on the attainable hydrogen price and the competition for use of climate-neutral hydrogen with the steel, energy and chemical industries.
- All the scenarios modeled show enormous expansion requirements for energy infrastructures up to 2035. According to the needs assessment, the main burden of the expansion will arise in the period from 2030 to 2035. Due to the time-consuming planning and approval procedures, the planning process for grid integration should begin as soon as possible. For charging locations on busy highways, a grid connection to the high-voltage grid will most likely be required, which entails implementation times of up to 10 years.
- In a comparison of the technology pathways, the investment requirements are highest for the mix of BEVs and O-BEVs. The lowest investment requirements result for a sole development of charging infrastructures in the BEV-only scenario. Nevertheless, the construction and operation of the energy infrastructures has been ensured in the analyses for all three technology pathways examined via an infrastructure levy added in the total costs of ownership.
- The present demand estimates clearly exceed the minimum requirements formulated in the AFIR for a development of alternative energy infrastructures in the EU. For the revision of the regulation in 2026, a higher level of ambition should be aimed at in order to ensure demand-oriented availability, in particular of public charging infrastructure for heavy-duty vehicles within the EU.

7 Conclusions and recommendations for action

The future transport market will be dominated by battery-electric heavy-duty vehicles.

Today's transport market is dominated by diesel trucks, which, with their long ranges and favorable fuel prices, have given transport companies a high degree of flexibility. If the actual consequential costs of the greenhouse gas emissions caused are priced into the operation of diesel trucks via a CO_2 price, the market potential of zero-emission drives is likely to outweigh them. Among these, market ramp-up modeling shows the highest potential for battery-electric heavy-duty commercial vehicles. Technical application potentials were taken into account depending on the limited ranges and the availability of public charging infrastructure. Fuel cell trucks achieve significant market shares only under optimistic assumptions of a future price development of climate-neutral hydrogen at refueling stations. All-electric overhead catenary trucks achieve market shares of around one-third in the event of electrification of an overhead line network of around 4,000 km in length on the highly frequented highway sections in Germany. Under the given framework conditions, the ramp-up of battery-electric trucks can be assumed to be almost certain, while greater uncertainties remain for fuel cell trucks and for overhead catenary trucks. In all scenarios, heavy-duty vehicle stocks are almost completely electrified by 2045.

Depot charging is the core and megawatt charging is the key to powering a heavy-duty battery-electric transportation system.

Rapid and targeted development of charging infrastructure for heavy commercial vehicles is the most important lever for the market ramp-up of battery-electric drives. An estimate of the demand for charging infrastructure reveals a high potential for charging operations at the depot amounting to around 55 % of the total energy demand. Public night-charging systems (NCS) account for another 25 % to cover multi-day tour profiles. In perspective, the remaining energy must be recharged at high power during the tour. To this end, the megawatt charging system (MCS) will enable the battery to be recharged within the legally prescribed rest period of 45 minutes after 4.5 hours of driving. By 2035, modeled demand results in a need for 2,000 MCS charging points and 40,000 NCS charging points. In particular, the development of MCS charging points at charging hubs along the federal highway network poses an enormous challenge, since a time-consuming and cost-intensive connection to the high-voltage grid is required and the short-term local demand or utilization of the charging points is difficult to estimate from today's perspective.

National climate protection targets for road freight transport require ambitions and measures that go beyond the European Union's minimum targets.

With its central location in Europe and its export-oriented industrial landscape, Germany plays an important role in European road freight transport. European Union legislation ensures congruent and interoperable technology development toward climate-neutral transport in 2050 via CO_2 fleet target values and specifications for the deployment of alternative energy infrastructures. German climate protection legislation with the goal of climate neutrality in 2045 sets even higher ambitions for the national transport market. Meeting the national targets requires a share of zero-emission powertrains in new German registrations of at least 60% in 2030 and nearly 100% in 2035. The supply and use of zero-emission commercial vehicles must be made correspondingly attractive. Important instruments include a CO_2 -based truck toll, the establishment of a framework for the targeted and rapid construction of charging infrastructure, and further support for vehicle and infrastructure procurement in the early market phase.

There is a high time pressure for the transition to zero-emission commercial vehicles and the development of the energy infrastructures in order to achieve the set greenhouse gas reduction target path.

Greenhouse gas emissions from road freight transport have increased by 30% over the last 30 years. Despite the start of electrification, the forecasts indicate that road transport volumes will continue to rise in the coming years, leading to a further increase in the number of diesel trucks in the fleet. A halving of greenhouse gas emissions compared with 1990 levels, as stipulated by climate protection legislation for the transport sector by 2030, places the electrification of road freight transport under enormous time pressure. At the same time, the vehicle and infrastructure market for electric heavy-duty vehicles is still in its infancy, while the heterogeneous transport market brings different prerequisites and preferences for the integration of electric drives into everyday practice. A pure focus on battery-electric drives is therefore not expedient as long as the technology has not yet been reliably established in practice. In addition to the construction of hydrogen refueling stations in accordance with the EU's minimum requirements, concepts for dynamic charging via *electric road* systems (e.g. overhead catenary systems) should be pursued in larger demonstration projects.

The electrification of road freight transport requires high private-sector investment, which must be supported by a clear political strategy and framework as well as a transparent information offering.

The switch to electric heavy commercial vehicles requires investments in further vehicle development, vehicle deployment, and the development and construction of energy infrastructures. For this, companies need planning certainty in the form of a clear political target and framework that ensures the ramp-up of electric heavy-duty vehicles. The time-critical development of a high-performance public charging infrastructure for electric heavy-duty traffic must begin promptly. Due to the long lead times, the planning of the network connection should be based at least on a demand estimate for the year 2035. In this context, an improved data basis through current mileage and trip surveys that address the requirements of electric commercial vehicles via specific characteristics, such as daily mileage, route structures, stopover times and locations, would be helpful.

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