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Transition pathways to decarbonise Germany's road sector with a focus on the role of technologies

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Summary

This study provides scenario modelling of the passenger vehicle market in Germany. The aim is to assess the role of available technologies to decarbonize the sector. The focus is on the three main technological options that are available, i.e., the use of battery-electric vehicles, fuel cell electric vehicles and e-fuels. The modelling is undertaken with VECTOR21 (Vehicle Technology Scenario Model) of the DLR Institute of Vehicle Concepts.

Keywords: alternative fuel, BEV (battery electric vehicle), emissions, fuel cell vehicle, PHEV (plug in hybrid electric vehicle)

1 Introduction

To limit global warming, governments around the world have pledged to decarbonize their economies. In Germany, the government has stipulated in 2019 the Federal Climate Change Act [1] to monitor and enforce ambitious CO_2 emission reduction targets. Under the current version of the Act [2], CO_2 emissions in 2030 are to be reduced by 65% compared to 1990. The long-term target for climate neutrality is set to be achieved by 2045. Transport CO_2 emissions, of which cars cause around 59% (2019) [3], are mandated to decrease from 150 million tonnes in 2020 to 85 million tonnes in 2030, equivalent to a reduction of 65 percent.

This is an ambitious target given that road transport-related CO_2 emissions were not subject to climate policies measure until recently. In the period from 1995 and 2019, only a modest reduction of 5% in CO_2 emissions per vehicle-km from improvements in the fuel efficiency of vehicles and a substantial increase in diesel cars was achieved. Even worse, this was counteracted by a substantial increase in vehicle kilometres travelled, resulting in an overall 5,1% increase in total emissions from cars over the same period [4]. With no structural changes occurring over the past three decades, in 2021 the road sector emitted 145 mio tonnes of CO_2, causing around one fifth of total CO_2 emissions in Germany [5]. This is equivalent to a 6,3% decrease in emissions compared to 1990; however, because of a drop-in travel demand due to extended periods of Corona measures in place over the past year (e.g. closure of schools, restaurants, shops).

A trend reversal in CO_2 emissions from cars and truck is expected due to strict CO_2 emission performance standards for cars and vans [6]. Set by EU regulation, manufacturers are obliged to reduce average CO_2 emissions of their vehicle sales. The current target is to achieve a reduction by 37,5% between 2030 and 2021 and stricter targets are already planned by the Commission (-55% by 2030 and 100% by 2035) [7].

The aforementioned EU regulation requires a technological response from vehicle manufactures. In fact, they are currently transitioning from the production of vehicles with internal combustion engines (ICE) to electrified vehicles, with a focus on battery electric vehicles (BEVs) and hybrid vehicles. An alternative technological approach for decarbonising the road sector is the replacement of fossil fuels with e-fuels. In fact, when synthetic diesel or petrol is produced using electricity from renewable energy, the well-to-wheel CO_2 emissions of road vehicles can be close to zero as CO_2 emitted during their operation was captured as part of the fuel production process.

This study investigates major technological options to decarbonise the car sector in Germany as part of scenario modelling. It provides scenario forecasts of the German car market from 2021 to 2045 according to four technological pathways, namely, “Elek”, “H2”, “E-Fuel” and a “Mix” scenario. “Elek” focuses mainly on direct use of electricity, scenarios “H2” and “E-Fuel” include also assumptions to promote fuel cell electric vehicles (FCEVs) and e-fuels, respectively. These three scenarios can be interpreted as “technology-push” scenarios. The idea of the scenario “Mix” is to promote a bundle of technologies.

The main objective of the modelling of the car market is to analyse technological options to achieve climate goals of the road sector in Germany. The analysis focuses on quantifying the CO_2 emission pathways of each scenario and the respective energy needs of the car sector. Another focus area is the simulation of different policy paths to achieve climate neutrality by 2045 in the car sector with a focus on CO_2 pricing, CO_2 fleet emission targets and a bonus-malus system for new vehicles. A crucial question is also the need for e-fuels to reach climate targets given the relatively asset life of cars in Germany.

The scenario forecasts of fleet development in Germany as presented in this paper was undertaken in 2021 as part of the Ariadne-Kopernikus project. As part of this study, the above mentioned scenarios were modelled by a range of models, covering all sectors of the German economy, as well as the climate system. Results of these scenario analysis of all models are described in [8]. This study focuses on the description of the modelling of the car fleet.

2 The German car market today and future development

In Germany (and globally), a main strategy for decarbonization is the replacement of road vehicles with ICEs with electrified vehicles. Germany is currently at the forefront of this development with 355,961 BEVs and 325,449 plug-in hybrid vehicles (PHEVs) registered in the period from January to December 2021, which is equivalent to 25% of total sales [9]. In addition, [9] reports the registration of 429,139 hybrid vehicles in 2021, including approx. 315,000 mild-hybrids; the remainder of them being full hybrid vehicles (HEVs).[1]

The electrification of vehicle sales in Germany has sped up substantially since 2020. In addition, in November 2021, the newly elected government announced the strategic goal to achieve 15 million electric vehicles on the road by 2030 [10]. Note that by the time of writing this study in April 2022, the three coalition parties of the German government have not yet agreed if this includes PHEVs or not, even though the coalition contract clearly states that these include only “full-electric” vehicle (BEVs). In any case, this foreshadows a rapid change of the automotive market towards an accelerated phase-out of vehicles with ICEs. This is also in line with company announcements including Opel, Daimler, Ford and Volvo to offer only BEVs by 2030.

1 Based on own analysis using KBA [7] and ADAC data [11]. Official data from KBA did not separate mild hybrid vehicles from full hybrid vehicles up until January 2022.

Currently, German OEM's product strategy currently clearly target BEVs and PHEVs to replace vehicles with ICEs. FCEVs are not part of their strategy (with the exception of BMW, announcing a small-scale production by the end of this decade in collaboration with Toyota); nor are HEVs part of the technological portfolio of German OEMs. The focus on BEVs and PHEVs can be demonstrated by the number of models by powertrain considering the five largest brands in terms of sales in Germany, i.e., VW (brand), Mercedes, BMW, Audi and Opel (refer to Table 1) [11]. These hold almost 50% of the German market share in 2021.

Table 1: Major OEMs/brands in Germany and their technology portfolio: number of models by powertrain (30 June 2021)[2]

	VW	Mercedes	BMW	Audi	Opel
Petrol	11	18	31	29	7
Diesel	7	14	20	18	7
HEV	0	0	0	0	0
PHEV	5	10	9	9	1
BEV	2	2	2	5	2
FCEV	0	0	0	0	0

The focus of the German car market on BEVs becomes even more apparent when analysing OEMs' announcements over the past 2 yers. To do this, we conducted an analysis of main car manufacturers in Germany. Of these, 17 OEMs/brands published a strategy by November 2021 with clear targets for future shares of electric vehicles. These OEMs/brands cover 82% of the German car market in terms of number of sales (based on 2020 sales data).[3] Because company announcements often included only information on one future year, nor is their understanding of "electric" cars always well defined, our forecasts are based on several assumptions. In consequence, we derived two different market forecasts, providing an upper and a lower estimation of electric vehicle shares (refer to Figure 1).

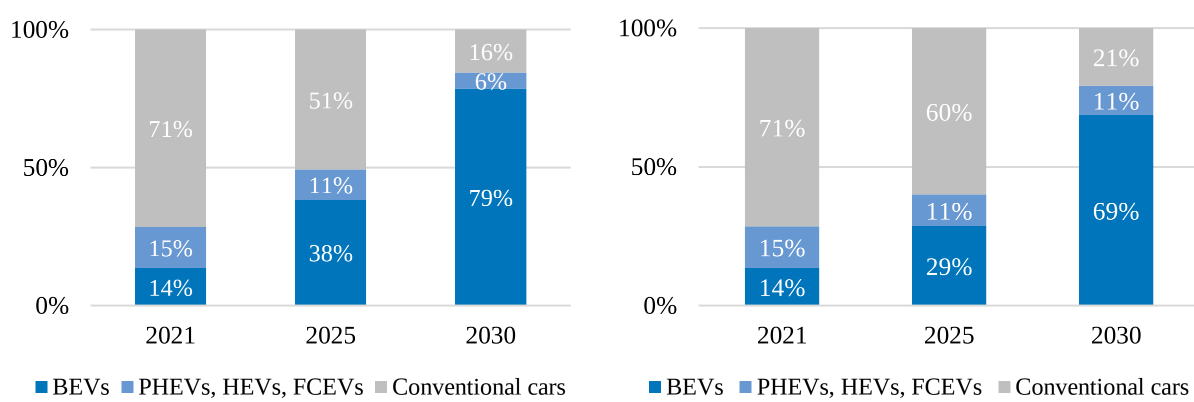

Figure 1 Company announcements of electric vehicles. Left: upper bound; right: lower bound. Sample: 17 OEMs/ brands covering 82% of the German car market in 2020[4]

It can be seen that by 2030, conventional cars (mostly petrol and diesel, including mild hybrids, and, to a negligible fraction LPG and CNG vehicles) could be replaced by up to 84% with electrified vehicles. By this

[2] Here, "model" refers to the name for the vehicle commonly used, such as VW Golf, Opel Corsa, Mercedes EQC, 1-er BMW etc.).
[3] These include (sorted by the number of sales in Germany in 2020): VW (brand), Daimler, BMW, Audi, Ford, Skoda, Opel, Renault, Hyundai, Fiat, Toyota, Peugeot, Volvo, Mazda, Porsche, Tesla and Honda.
[4] Due to a large number of OEMs active in Germany, we focused on the largest OEMs only in number of sales in Germany in 2020.

time, the market share of fully electric vehicles could ramp up from today's 14% [9] to 70-80% of car sales according to OEMs announcements. Again, note that this only refers to 82% of the German market.

PHEVs are in the portfolio, but to a much smaller extent; together with FCEVs and HEVs, these cover between 6-11% in 2030. Only Toyota and Hyundai include currently FCEVs in their portfolio; by the end of this decade, BMW will also bring to market a fuel cell model.

While German OEM's company announcements clearly point to BEVs market dominance, the market introduction of fuel cell technology is imminent in the heavy truck sector (e.g., Toyota, Hyundai, Daimler, Volvo). Therefore, a technological transfer in from the truck to car sector may be possible in the farer future.

Similar to FCEVs, the role of e-fuels in the car sector in Germany and Europe is also not clear yet. The current version of the EU CO_2 fleet regulation [6] does not allow for the use of climate-neutral e-fuels to meet OEMs fleet targets, nor is this option included in the amendment proposed by the European Commission in July 2021 as part of the fit-for-55 package [7]. The German government is in line with the exclusion of e-fuels to meet CO_2 fleet targets.[5]The German Association of the Automotive Industry (Verband Deutscher Automobilindustrie, VDA) lobbies for an accelerated market ramp-up of e-mobility, however, in contrast to the German government, they consider that e-fuels should occupy a prominent role for decarbonising the vehicle stock.

To investigate the role of technologies and other policy measures for meeting German climate goals, scenario modelling is considered a suitable methodology. It allows to investigate flow-on effects of different decarbonisation pathways on CO_2 emissions and energy consumption and identifies the pathways' regulatory and infrastructural requirements. Several major scenario studies were conducted on behalf of Ministries [8] [12], the industry lobby [13] and other organisations [14] [15] in 2021. These studies commonly model technology-push scenarios, defining worlds with different focuses on technologies to meet climate goals across all sectors. A different approach is taken by the insightful study of FVV [16], prepared in collaboration among automotive and fuel industry participants. Rather than investigating scenarios with a balanced role of technologies to reach climate neutrality, the studies investigates "100 % worlds", where the entire transport sector is solely fuelled by a respective fuel / drivetrain (such as 100% BEV or 100% methanol.

3 Methodology

3.1 Scenarios assessed

The study assesses four possible technology pathways, i.e. pathways that emphasize either direct electrification, green hydrogen, e-fuels diffusion, or a technology mix, namely, "Elek", "H2", "E-Fuel" and a "Mix" scenario. A commonality of all scenarios is a strong deployment of BEVs and (initially) PHEVs, in line with the current market development. However, in the "Elek" scenario, a faster ramp-up of these drivetrains is assumed due to optimistic assumptions regarding future battery cost and fast build-up of the infrastructure compared to the H2 and E-Fuel scenario.

3.2 Fleet model

To investigate the role of different technologies in the passenger vehicle sector in Germany to meet climate goals, we deployed the VECTOR21 (Vehicle Technology Scenario Model) of the DLR Institute of Vehicle Concepts

[5] The government elected for the period 2021-2025 stated in their coalition agreement that the they agree with the European Commission's plans to enforce that by 2035 only emission-free vehicles can be registered in the EU (i.e. only BEVs and FCEVs). In addition, they highlight that "outside the EU CO_2 fleet regulation" they "would work to ensure that only vehicles that can demonstrably be fueled with e-fuels can be newly registered". The exact wording is: „Außerhalb des bestehenden Systems der Flottengrenzwerte setzen wir uns dafür ein, dass nachweisbar nur mit E-Fuels betankbare Fahrzeuge neu zugelassen werden können.“ [8].

[17].[6] This tool allows to estimate scenario-based forecasts of car sales with a focus on technologies' plausible developments (such as expected improvements of the battery technology) in order to provide insights into the technologies market potentials. VECTOR21 is an agent-model depicting a range of vehicle customer groups differentiated by their driving behaviour (such as annual mileage) and preferences (such as the availability of charging infrastructure or technical aspects of vehicles). The vehicle market supply is represented by reference vehicles that differ in terms of their techno-economic characteristics based on 2021 actual data. The model includes reference vehicles for all relevant powertrains currently on the market (e.g. diesel and gasoline; plug-in hybrid, battery electric, hydrogen) and different vehicle segments (small, medium and large).

All pathways rely on specific projections of available quantities of green hydrogen and e-fuels until 2030 as well as vehicle technology and energy carrier cost projections. Additionally, each scenario is underpinned by a specific set of policies to foster the introduction of new vehicle technologies and e-fuels. The main scenario assumptions are summarised in the following table.

Table 2: Main assumptions and input for fleet modelling with VECTOR21

	Mix	Elek	H2	E-Fuel
CO_2 price (Euro2020 / tonne CO_2)	2025: 100 2030: 200 2045: 500	Same as Mix	Same as Mix	Same as Mix
CO_2 EU fleet emission targets	2030: -50% reduction compared to 2030. Post 2030: Reduction to meet 90% CO_2 emission reduction by 2050 compared to 1990 (according to targets set in the Green Deal [18]).	Same as Mix	Same as Mix	Same as Mix, with the exception that from 2030, vehicles with ICEs are considered by the regulation as zero-emission vehicles if they are fuelled with e-fuels. This is possible for up to 10% of vehicles of an OEMs fleet.
Energy tax (Euro2020)	Petrol: 0,65€/l in 2020; assumption that rate remains nominally constant in line with historical trend Diesel: 0,47€/l; assumption that rate remains nominally constant in line with historical trend H2 and e-fuels tax exempt until 2030, 50% until 2035. From 2035 equal to fossil fuels.	Same as Mix	Same as Mix	Same as Mix
Drop-in e-fuel share	2023: 1% 2030: 2% Increasing share over time reaching >90% by 2045 (the remainder consists biofuels)	Same as Mix	Same as Mix	2023: 1% 2030: 10% Increasing share over time reaching >90% by 2045 (the remainder consists biofuels)
H2 Infrastructure and charging points	Charging infrastructure for BEVs/PHEVs is complete by 2030; H2 infrastructure set up is 100% finalised in 2035.	Accelerated build-up of the charging infrastructure for BEVs/PHEVs by 2025; completed by 2030; no substantial extension of today's existing 100 H2 fuelling stations	Accelerated build-up of the charging infrastructure for BEVs/PHEVs by 2030; completed by 2035; H2 infrastructure set up is 100% finalised in 2030.	Accelerated build-up of the charging infrastructure for BEVs/PHEVs by 2030; completed by 2035; H2 infrastructure set up is 100% finalised in 2040.

[6] An overview of the tool is also provided here: https://verkehrsforschung.dlr.de/en/projects/vector21.

Technology cost assumptions (Euro2020)	Battery: reduction to 90 Euro/kWh by 2030 [19]; fuel cell system: reduction to 58 Euro/kW by 2050 ([20]; own assumptions)	Battery: reduction to 54 Euro/kWh by 2030 [21]; fuel cell system: reduction to 58 Euro/kW by 2050 ([20]; own assumptions)	Battery: reduction to 90 Euro/kWh by 2030 [19]; fuel cell system: reduction to 58 Euro/kW by 2030 ([20]; own assumptions)	Same as Mix
Electricity price home charger (Euro2020)	0,35 Euro/kWh (assumptions), constant over time	Gradual reduction to 0,29 Euro/kWh by 2045	Same as Mix	Same as Mix
H2 (green) price at fuel station (Euro2020/ kg)	2030: 7,80 Euro/kg 2050: 5,70 Euro/kg (based [22])	Same as Mix	Same as Mix	Same as Mix
BEV/PHEV purchase bonus ("Umweltprä mie")	According to 2021 incentive scheme, no change until 2025 (e.g. 9.000 Euro for BEVs/FCEVs in the small- /medium segment)	Same as Mix	Same as Mix	Same as Mix

Based on the estimations of new fleet development with VECTOR21, the project team derived stock development. Final energy demand and total CO_2 emissions of the German transport sector were derived merging stock development and mobility demand. The latter was calculated using DEMO (DEutschlandMOdell = German Transport Model).

3.3 Travel demand model

The future developments of transport demand were estimated for the four scenarios deploying DEMO (DEutschlandMOdell = German Transport Model) [23] of the DLR Institute of Transport Research.

DEMO is a macroscopic, synthetic, multimodal transport model that forecasts travel demand in Germany with a high degree of spatial differentiation. Both short- and long-distance travel is represented in the model, with all modes of transport (car, rail, bus, plane, public transport, walking, cycling) being considered. Main input data for DEMO is differentiated population and land-use data (e.g. workplaces, shopping locations etc.), travel behavior parameters and preferences derived from empirical data (e.g. household travel surveys, value of time studies), and network-based impedances (travel times, distances, user costs etc.). The model is structured similarly to a traditional four-step model, with trip generation, destination and mode choice, and traffic assignment. The model outputs include mode shares, passenger and vehicle kilometers by mode, but also traffic loads on the network considered.

4 Results

The following diagram presents fleet development, the major output of VECTOR21 modelling, for the four scenarios considered in this study.

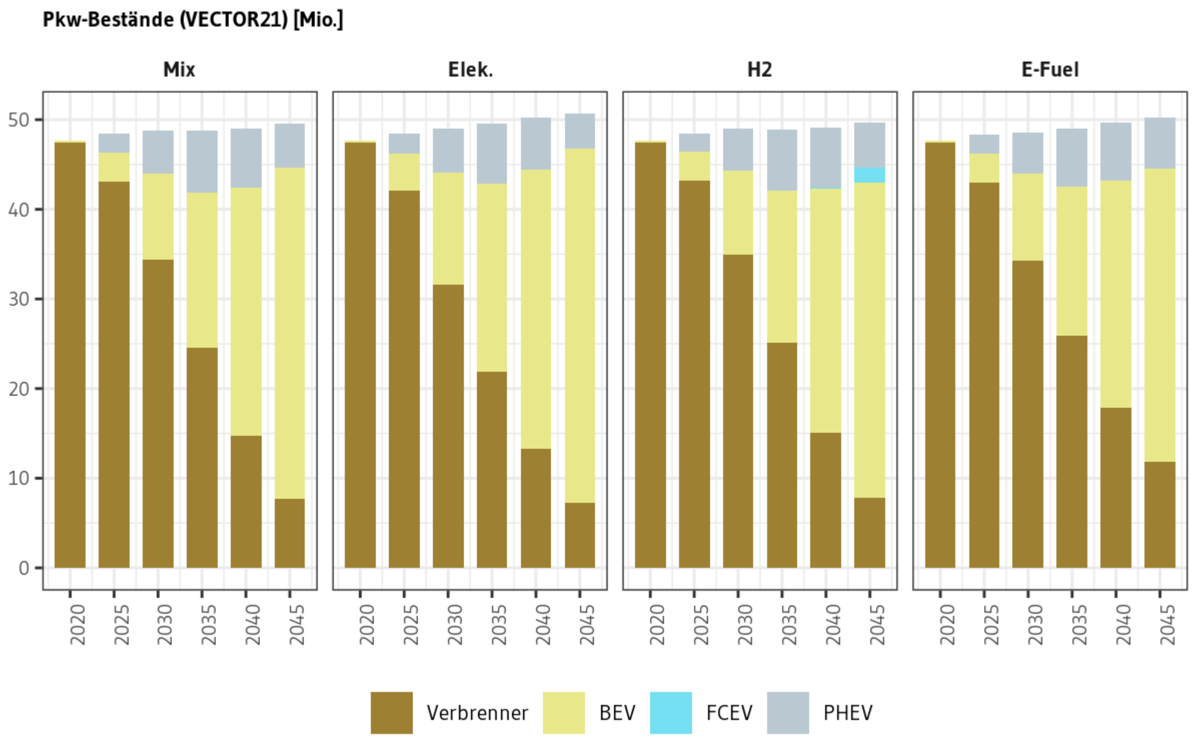

Figure 2: VECTOR21 results: development of the German car stock (in mio vehicles)

BEVs are the dominant car technology, beginning from 2030, across all scenarios considered. The fastest diffusion of BEVs can be seen in Elek, driven by optimistic assumptions regarding future battery costs (54 Euro2020 /kWh in 2030) and the completion of the charging network by 2030. In the 2020s, across all scenarios, PHEVs gain a substantial market share. However, by the end of the 2020s sales numbers stagnate due to BEVs gaining competitive advantage (mainly regarding costs and a gradual improvement of the recharging system). As compared to BEVs and PHEVs, FCEVs can be considered a technology of the future. Under optimistic assumptions (tested in H2), FCEVs become competitive for some customer segments in the 2040s. This requires the build-up of the H2 charging infrastructure and a substantial decrease in vehicle technology costs, namely fuel cells. The model results also show that e-fuels are required across all scenarios to decarbonize the car sector. Depending on the scenario, in 2045 there are still 11.1 to 17.5 ICEs on German roads.

Building on the development of the car fleet, energy consumption and CO_2 emission are calculated. The results show that the electrification of the car fleet leads to substantial emission reductions by 2030. Direct electrification (Elek) contributes the largest share to reducing CO_2 emissions until 2030. However, none of the scenarios meets the required sector target in 2030. Even increased projected e-fuel drop-in rates (assumed under the E-Fuel scenario) do not guarantee to meet the target. Especially long holding times of passenger cars prevent more substantial CO_2 emission reductions.

The following Figure 3 shows the development of CO_2 emissions of the whole transport sector. Note that this includes car fleet development (as shown in Figure 2), but also truck development estimated with VECTOR21 truck model (not presented in this paper) and the rail sector.

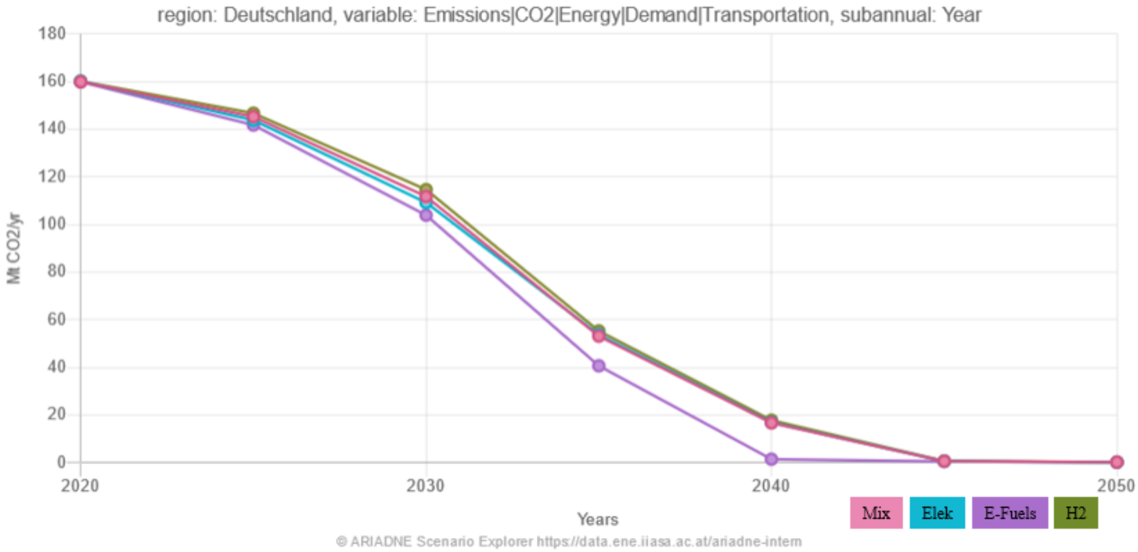

Figure 3: CO_2 emissions transport sector

4.1 Updated simulation

Scenario forecasts start usually from taking current regulations and price structures as a starting point and then, designing reasonable developments depending on the scenario storyline. Since the model runs presented in Figure 2 undertaken in June-August 2021, the European Commission has proposed to phase out vehicles with ICEs by 2035. In addition, in April 2022, the Federal Ministry for Economic Affairs and Climate Action has proposed to cancel purchase subsidies for PHEVs from January 2023 and a reduction in purchase subsidies for BEVs/FCEVs. In light of these new developments, we conducted an updated model run of the "Mix" scenario. It can be seen that

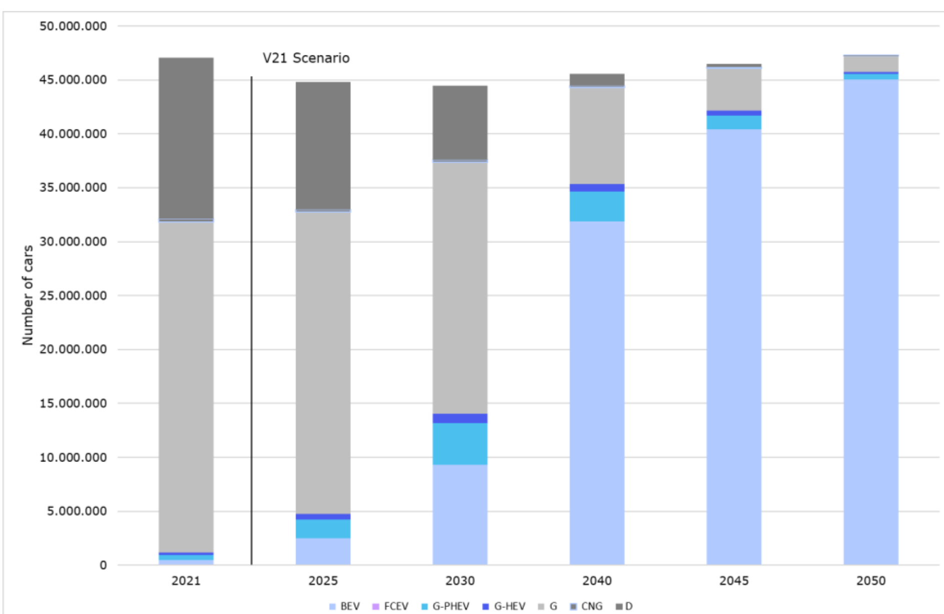

Figure 4: Updated model run "Mix": fleet development

The most substantial difference to the results of the original “Mix” is the much accelerated replacement of diesel/petrol vehicles with BEVs, starting from 2030, resulting in merely 4,2 mio vehicles with ICE in 2045.

5 Conclusions

The results show that BEVs are the dominant vehicle technology of the future in Germany, while PHEVs can be considered a transitional technology, expected to lose their competitive advantage as soon as recharging infrastructure is established and costs for BEVs with large batteries further decline. In addition, with future CO_2 fleet regulations in Europe requiring zero emissions at some point (proposed by the European Commission by 2035), PHEVs seize to represent a technological option. This is different to FCEVs. However, FCEVs enter the market only under optimistic assumptions analysed under the H2 scenario. Because in 2021 this technology (especially fuel cells and tanks) lags behind technological features of BEVs (especially batteries), it is not clear yet if the technological development of FCEVs are able to catch up at any point in the future in the car sector. Having said that, some market players including Daimler, Volvo, Toyota and Hyundai focus on trucks fuelled by hydrogen, making it a possible option that these technologies are adopted eventually in the car market.

The results of the modelling also showed that a technology change towards zero emission vehicles by itself does not guarantee meeting German transport sector 2030 targets, but should be complemented by other measures including mode shift to cycling, walking and public transport.

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Nomenclature

BEV Battery Electric Vehicles
FCEV Fuel cell electric vehicle
HEV Full hybrid vehicle
ICE Internal combustion engine
PHEV Plug-in hybrid vehicles
VDA Verband Deutscher Automobilindustr*ie*

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