Pathways for decarbonizing the road transport sector – the example of Germany[1]

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Introduction

In order to achieve a transformation to a long-term low-carbon economy, the European Union has set climate and energy targets to reduce greenhouse gas (GHG) emissions as well as increase the share of renewable energy generation (RES). However, it is not uncommon for member states to define their own climate and energy targets, which then become embedded in this European framework. For example, the German government announced ambitious goals in its Energy Concept aimed not only to decarbonize the energy sector as a whole but also to transform specific sectors. The sector-specific renewable target for the electricity sector, in particular, has helped to trigger the rapid growth in renewable generation seen in Germany over the past several years. As a result, the transformation of the electricity sector has greatly contributed to reducing national GHG emissions.

While several other sectors have jumped on the bandwagon, not every sector has committed to decarbonization. In fact, the amount of carbon emissions emitted in the German road transport sector has remained constant since 2005 at 150 million tons of CO2-eq per year. Although the Energy Concept mandates a 40% reduction in final energy consumption for the transport sector by 2050, there appears to have been little to no restriction on GHG emissions for this sector over the past decades. More recently, however, initiatives have been taken to instigate an energy transformation in the transport sector, including a sector-specific decarbonization target in the 2016 "Klimaschutzplan". In addition, technological advances in battery storage and electric vehicles have led to increased interest in zero-emission vehicles and a growing demand for alternatives to gasoline and diesel fuels. Production of synthetic gases and liquids via power to gas and power to fuel is one such alternative, capable of not only supplying 'carbon-neutral' fuels for the transport sector but also providing flexibility to the electricity sector. With sector-specific targets being defined and new technologies entering the market, it becomes increasingly important to understand the economic impacts of decarbonizing the road transport sector in Germany. Moreover, interdependencies between sectors due to electrification or gas-applications in transportation may lead to distribution effects, which may impact the overall transformation to a long-term low-carbon economy.

The study at hand seeks to address these issues by examining multiple pathways for decarbonizing the German road transport sector. Using a large-scale linear investment and dispatch model combining the European electricity, heat and road transport sector, four different scenarios are examined. In particular, the effect on the long-term vehicle mix in Germany under a sector-specific CO_2-cap—as is currently being discussed by the German government—is compared to the results when only a fleet target (in g CO_2/km) on new vehicle registrations is introduced—as the European Commission has already done for years. The model will yield the cost-optimal solution under each of these regulatory schemes, minimizing the total costs of the electricity and heating sectors as well as the total costs for the vehicles, fuel use and infrastructure needed to reach the CO_2 reduction goals. At the same time, the need for investments in infrastructure for new vehicles will be

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reexamined. In other words, in two scenarios, the model will assume that the necessary infrastructure for low- or zero-emission vehicles will be available and does not affect the model's investment decisions. This should simulate a policy in which, e.g., the German government provides financial support by investing in the infrastructure for an alternative vehicle technology.

Literature Background

Decarbonization

Literature provides many sources for energy transition modeling. Söderholm et al. (2011) summarize modeling attempts for transition pathways in a comprehensive overview and describe that research focusses on transforming an economy into a less carbon-intensive economy over time by commonly applying cost-minimizing bottom up models. Kitous et al. (2010) and van Vuuren et al. (2010), for instance, run simulations on the supra national level stressing that primary energy consumption will double and conventional generation will successfully be replaced by renewables. In contrast, Kirsten (2014), Gawel and Hansjürgens (2013) as well as Lindenberger et al. (2016) focus on the transition of the German energy system and the interaction between national and international policies. Gawel and Hansjürgens (2013) find that a steadily increasing share of non-dispatchable electricity from renewable sources is jeopardizing the stability of the future European energy system. Kirsten (2014) as well as Lindenberger et al. (2016) point out the difficulties in reaching its ambitious goal of reducing GHG emissions. What remains to be answered from an integrated analysis for GHG reduction is if and how the road transportations sector, if coupled with the electricity market, is decarbonized and what future technologies will be deployed if the sector is subject to emission reduction. To determine the optimal vehicle fleet, assumptions about fuel, infrastructure and vehicle costs, efficiencies and emission factors have to be taken into account (c.f. data section).

On a European level, van de Zwaan (2013) studies potential pathways and concludes for the road transportation sector that investments in establishing an extensive hydrogen distribution network are not optimal due to their capital-intensive costs. Gül et al. (2009) support this finding; however they add to the analysis of Gül et al (2009) that a very stringent climate policy might nevertheless trigger at least some hydrogen investments in the long run. By using a bottom-up model, a possible roadmap for the deployment of bio-fuel blends, technological learning and the deployment of hybrids, battery electric, plug-in hybrid and fuel cell vehicles is in depth analyzed by Pasaogluc et al. (2012), concluding in a similar manner that hydrogen technologies will not belong to the early movers in the road transportation sector.

Energy Market Modelling

Energy market modelling mainly distinguishes between regions (i.e. one country of more) and sectors (i.e. electricity, gas, heat or transport), whereas lately modelling attempts surrounding the coupling of sectors have become increasingly important (for instance Schaber et al. (2013)). Reasons for that may be plentiful, however one key lesson learnt from a sector coupling analysis is that a cross-sectorial analysis enables researchers to study synergies among the value chain of the sectors.

Literature provides plenty of studies that consider the global, European and national level. Most of them build on modeling different assumption-driven scenarios for the energy market up to a certain point in time (mostly up to 2020 or 2050). These assumption-driven scenarios are based on quantitative projections of energy consumption and supply, fuel prices, certificate-trading systems and their implicit CO2 prices. Furthermore, it is often common to reflect the technological development by using cost degression assumptions over time, thereby implicitly assuming that different technology improvements can be realized for each technology. Other variables determining the overall future energy trend can be found for instance in Newell and Iler (2013).

Although many of these assumptions used are similar, one key difference lies in the design of the studies themselves. Whereas some studies are target-oriented ((Newell and Iler (2013), UBA (2013) or Spiecker and

Weber (2014)), implying that reaching a certain target will lead to minimum costs, others study the development of the energy market given the current policy framework (EC (2014)). By doing so, the authors avoid making predictions on policy proposals that have not yet been decided. The latter provide a useful baseline against which other scenarios can be measured.

Methodology

The quantitative analysis is performed using a large-scale linear investment and dispatch model combining the European electricity, heat and road transport sector. The model determines the cost-efficient investment and dispatch strategy for meeting the electricity, road transport and heating demand of each country in 5-year time steps from 2010 until 2050. The accumulated discounted total system costs are minimized, subject to several techno-economic assumptions explain in detail below. The cross-sectorial aspect of the model allows us to determine a cost-minimal energy mix given constraints such as carbon emission targets and energy balance. By accounting for these constraints, the European road transport sector and its interlinkage with the electricity, market model is simultaneously optimized, allowing for an integrated analysis yielding a cost-minimal, welfare-optimal solution.

The model developed in this study is an extended version of the dynamic linear electricity system optimization model of the Institute of Energy Economics (University of Cologne), as presented in Richter (2011), Fürsch et al. (2013) and Jägemann et al. (2013). In particular, both the European road transport sector as well as cross-sectional technologies such as power to gas and power to fuels were integrated into the existing model. The key assumptions, parameters and constraints for each of these modules are given below. For completeness, a short overview of the European electricity market model is also included.

Modeling the European Electricity Sector[3]

The model covers all 28 countries of the European Union, except for Cyprus and Malta, but includes Norway and Switzerland. The investment decisions and generation profiles for a wide range of power plants are optimized endogenously. These include conventional, combined heat and power (CHP), nuclear, onshore and offshore wind turbines, roof and ground photovoltaic (PV) systems, biomass (CHP-) power plants (solid and gas), hydro power plants, geothermal power plants, concentrating solar power (CSP) plants (including thermal energy storage devices) and storage technologies (pump, hydro and compressed air energy (CAES)).[4] Technological improvements in, e.g., efficiency are taken into account using vintage classes. These are then included in the model as an additional technology option that is only available at a certain point in time onwards.

All cost assumptions for technologies listed above are taken from the databank at the Institute of Energy Economics (University of Cologne). Key cost factors are investment, fixed operation and maintenance and variable production costs as well as costs due to ramping thermal power plants. As previously stated, the objective function of the model will seek to minimize the accumulated discounted total system costs.[5]

The large interconnector capacities are taken into account via one node per country. Hence, the model covers 28 countries connected by 65 transmission corridors. Existing and future extensions of net-transfer capacities are exogenously defined and may in some cases limit the power exchange across country borders. This data has been

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[3] This subsection was adapted from Jägemann et al. (2013)

[4] The use of lignite and biomass sources (solid and gaseous) is restricted by a yearly potential in MWhth per country. Wind and solar are also (in some countries) subject to minimum and maximum deployment levels to ensure a realistic outcome (ENTSO-E, 2015a).

[5] The total system costs do not include investment costs for electricity grid extensions nor operational costs for grid management. Investment costs occur for new investments in generation and storage units and are annualized with a 5% interest rate for the depreciation time. The fixed operation and maintenance costs represent staff costs, insurance charges, interest rates and maintenance costs. Variable costs are determined by the fuel price, net efficiency and total generation of each technology. Depending on the ramping profile additional costs for attrition occur. CHP plants can generate income from the heatmarket, thus reducing the objective value (Jägemann et al, 2013).

taken from the Ten Year Network Development Plan “TYNDP” (ENTSO-E, 2015b), the German Netzentwicklungsplan (BNetzA, 2016) and the E-Highway 2050 report of the European Commission (Pestana, 2015; RTE, 2015).[6]

Moreover, the model considers several subregions within the countries, which differ with regard to the hourly electricity feed-in profiles and the achievable full load hours of wind turbines (onshore and offshore) and solar power plants (PV and CSP) per year. Overall, the model distinguishes between 47 onshore wind, 42 offshore wind and 38 solar subregions across Europe. The hourly electricity feed-in of wind and solar power plants per subregion are based on historical hourly wind speed and solar radiation data by EuroWind (2011).[7] The deployment of wind and solar power technologies is restricted by a space potential in km^2 per subregion.

On the demand side, the current and future values per country (in MW) are taken from TYNDP (ENTSO-E, 2015b) and E-Highway 2050 from the European Commission (Pestana, 2015; RTE, 2015) [8]. The exogenous electricity demand does not take into account any additional electricity demand from other sectors such as transport or heating, as the additional demand for these sectors is determined endogenously by the model. Hourly electricity demand is generated using an hourly structure developed at the Institute of Energy Economics (University of Cologne). The corresponding electricity price is a model output, as it depends on the endogenous, cost-minimal generation mix.

Modeling the European Road Transport Sector

The road transport sector is divided into three groups: passenger vehicles (PV), light-duty vehicles (LDV) and heavy-duty vehicles (HDV).[9] Similar to the approach for the electricity sector, technologies are defined for each of these road transport groups. In this case, however, technologies can be understood as motor types such as gasoline motors, natural gas motors, battery electric vehicles (BEVs), FCEVs, etc. Figure 1 gives a schematic overview of the motor types analyzed in this study.

[6] Data from the TYNDP 2016 (ENTSO-E, 2015b) was used for all countries in 2020 and for all countries except Germany in 2030. The NEP (BNetzA, 2016) was used for Germany for the years 2030 und 2040. The E-Highways 2050 „Small&Local“ was used for all countries except Germany in 2040 and all countries for 2050.

[7] While the securely available capacity of dispatchable power plants within the peak-demand hour is assumed to correspond to the seasonal availability, the securely available capacity of wind power plants (onshore and offshore) within the peak-demand hour (capacity credit) is assumed to amount to 5%. In contrast, PV systems are assumed to have a capacity credit of 0% due to the assumption that peak demand occurs during evening hours in the winter. A peak-demand constraint ensures enough back-up capacity to meet security of supply requirements given a high share of fluctuating renewables (Jägemann et al., 2013).

[8] For all countries, the "Expected Progress" Scenario (from the TYNDP 2016) is used for 2020 and the "Constrained Progress" Scenario for 2030 (from the TYNDP 2016). The "Small&Local" Scenario (from E-Highway 2050) is used for the years 2040 and 2050.

[9] Light-duty vehicles are considered to weight less than 3.5 tonnes, heavy-duty vehicles more than 3.5 tonnes. Motorbikes, scooters and bicycles are excluded from this analysis, as are buses.

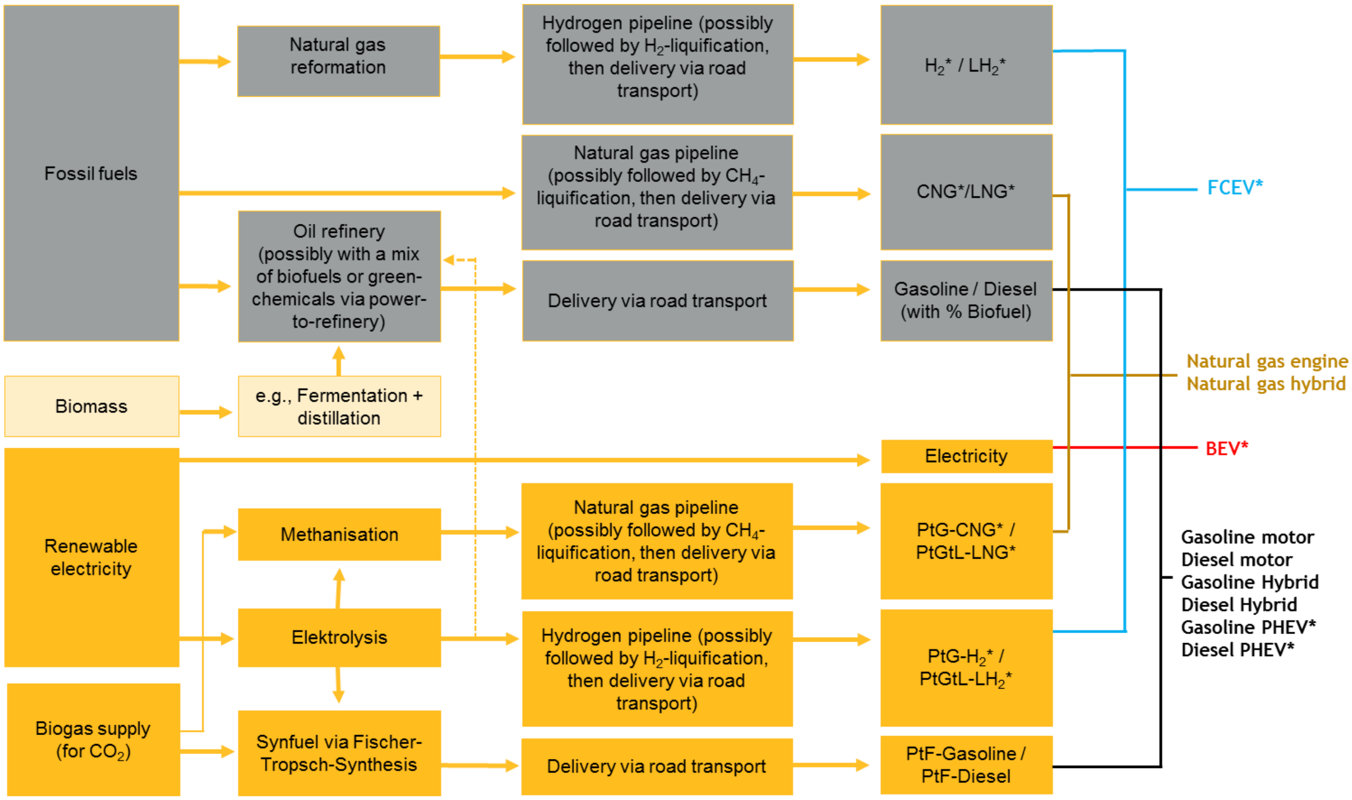


Figure 1: Schematic overview of the road transport module

** BEV: Battery Electric Vehicles, FCEV: Fuel Cell Electric Vehicles, PHEV: Plug-in Electric Vehicles; H2: Hydrogen Gas, LH2: Liquid Hydrogen, CNG: Compressed Natural Gas, LNG: Liquid Natural Gas*

Note: Non-plug-in hybrids with gasoline, diesel and natural gas use a battery to assist the car in accelerating, braking and other non-driving features

A key factor of this analysis is that we consider the entire production process, from the raw energy source to the automobile itself ("well-to-wheel"). Figure 1 demonstrates the different fuel types and their production as well as delivery processes, with the grey area indicating the fossil fuel power trains and the orange area the "zero carbon" as well as the "carbon-neutral" power trains. These include not only electric power trains but also the production of power-to-gas compressed natural gas and power-to-gas-to-liquid natural gas (PtG-CNG, PtGtL-LNG), power-to-gas hydrogen gas and power-to-gas-to-liquid hydrogen (PtG-H_2, PtGtL-LH_2) as well as power-to-fuel synthetic gasoline and power-to-fuel synthetic diesel (PtF-Gasoline, PtF-Diesel). Each of these technologies as well as how they are simulated in the model are described in the next subsection.

As our focus is on decarbonizing the road transportation sector, it is key that all carbon emissions be accounted for. Technologies such as methanisation and Fischer-Tropsch-synthesis, for example, produce carbon-based fuels that, via combustion, will emit carbon dioxide into the atmosphere—yet the process itself will also consume carbon dioxide in order to transform hydrogen to methane, octane (gasoline) or hexadecane (diesel). This gives these technologies an advantage compared to their conventional alternatives because the production of such "green fuels" can contribute to decarbonization by displacing carbon-heavy fuels. Carbon emissions from delivery from the green fuel to the gas station via tanker, for example, are still considered in the analysis.

Because of the complexity of the analysis, many assumptions must be made and a large dataset is required. The parameters can be separated into three categories: vehicle technology, fuel type and infrastructure. Table 1 gives an overview of the key parameters per category as well as the primary sources for the data used in the analysis.

Category	Parameter	Unit	Changes over time?	In which direction?	Sources
Vehicle Technology	Total driving distance per year	billion km	Yes	↓	Schlesinger et al. (2014), EC (2013)
	Annual driving distance per vehicle per year	km/vehicle per year	No		EC FCH JU (2010), KBA (2015), Schlesinger et al. (2014), EC (2013), Rhenus Logistics (2007), ifeu (2012)
	Vehicle lifetime	years	No		EC FCH JU (2010), Schlesinger et al. (2014), ifeu (2012)
	Purchase price	Euro/km	Yes	↓↓	EC FCH JU (2010), Growitsch et al. (2013); Rhenus Logistics (2007), Shell (2010), Dodds et al. (2014a, 2014b) , ifeu (2012)
	O&M costs	Euro/km	Yes	↓	EC FCH JU (2010), Dodds et al. (2014a, 2014b), Rhenus Logistics (2007) , ifeu (2012)
	Fuel consumption	kWh/km	Yes	↓↓	Dodds et al. (2014a, 2014b), Schlesinger et al. (2014) , ifeu (2012)
Fuel Type	CO2 factor	kg CO2-eq/kWh-fuel	No		Edwards et al. (2014)
	Fuel price	Euro/kWh-fuel	Yes	↕	ewi ER&S, DLR (2014), EIA (2015)
	Production costs (fossil fuels)	Euro/kWh-fuel	Yes	↑	EIA (2015)
Infrastructure	Capital costs	Euro/vehicle	Yes	↓	Dodds et al. (2014a, 2014b), EC FCH JU (2010)
	O&M costs	Euro/vehicle	Yes	↓	Dodds et al. (2014a, 2014b), EC FCH JU (2010)
	Distribution costs	Euro/vehicle	Yes	↓	Dodds et al. (2014a, 2014b), EC FCH JU (2010)
	Infrastructure lifetime	years	No		Dodds et al. (2014a, 2014b)

Table 1: Overview of the key parameters and sources used in the road transport module

The vehicle technology parameters tend to vary not only according to the motor but also across road transport group (PV, LDV, HDV). For example, the purchase price, O&M costs and fuel consumption vary greatly not only between a diesel vehicle and a FCEV but also between a passenger vehicle and a heavy-duty vehicle. This variation increases competition: as the model attempts to decarbonize the complete road transport sector at minimal cost, different vehicle technologies will compete not only within their road transport group (e.g., diesel motor v. FCEV) but also against the CO2 abatement costs of the other groups (e.g., heavy-duty vehicle with a natural gas motor). The vehicle lifetime and annual driving distance per vehicle per year, on the other hand, are consistent across vehicle technologies. Across road transport groups, however, these vary drastically: Whereas a passenger vehicle may drive for 15 years on a road, light- and heavy-duty vehicles are not expected to live more than 10 years. This is in part due to the large differences in yearly driving distance, assumed to be 13,800 km for PVs, 21,800 km for LDVs and 70.000 km for HDVs.

One key parameter to note is the total driving distance per year. This value sets the annual demand for vehicles in each road transport group in each country up to 2050. It represents the number of vehicles multiplied by the yearly driving distance of the PV, LDV or HDV. Analogous to the electricity model, this parameter plays a critical part of the equilibrium condition. For some countries, such as Germany, this demand is expected to stay rather constant, with a slight decrease in the long term as less cars the number of cars on the road.

The parameters for fuel type will differ depending on how the fuel was produced, e.g., whether the hydrogen gas was created by power-to-gas or from methane reformation. In this case, the CO2-factors would differ as the well-to-wheel emissions take into account the CO2-intensive reformation process. In terms of fuel price, the values are mostly the same as those assumed in the electricity model. Gasoline and diesel are subject to additional production costs, e.g., from refining crude oil. The electricity price for BEVs and PHEVs are endogenously determined by the electricity market model described in the subsection above.

Infrastructure is, in the model developed for this analysis, considered to be solely dependent on the final fuel (diesel, gasoline, natural gas, hydrogen, electricity), regardless of how it was produced. In other words, a natural gas vehicle running on PtG-CNG will yield the same capital costs for infrastructure as a natural gas car running on conventional CNG. Within this study, infrastructure refers to gas stations, electric charging stations (50% public, 50% home charging), distribution networks for liquid fuels (via tanker transport) as well as pipeline additions (for hydrogen and natural gas).[10]

It should be noted that, similar to the electricity model, the road transport module also covers all 28 countries of the European Union, except for Cyprus and Malta, but includes Norway and Switzerland. However, the research question focuses on the impact of decarbonization schemes for the road transport sector in Germany. Therefore, although all countries are simulated in the model, the results presented in the sections below will focus on the vehicle mix in Germany.

Modeling Power-to-Gas and Power-to-Fuel Technologies

Electrolysis, methanisation and Fischer-Tropsch synthesis were integrated into the road transport module as well as the electricity model.

Scenario Definitions

In order to analyze the pathways for decarbonizing the road transport sector, four scenarios are considered. These are summarized in Table 2.

Scenario	European CO_2-Cap	National CO_2-caps in road transport sector?	Fleet target for new registrations?	Infrastructure support?	Time Horizon	Spatial Resolution
Scenario I	Yes	Yes	No	No	2050	Europe
Scenario II	Yes	No	Yes	No	2050	Europe
Scenario III	Yes	Yes	No	Yes	2050	Europe
Scenario IV	Yes	No	Yes	Yes	2050	Europe

Table 2: Scenario Matrix

In all scenarios, a European-wide CO2-cap covering all sectors is taken into account. For Scenarios I and III, a national CO2-cap (% reduction) for the road transport sector in each country is set for 2020, 2030 and 2050. A similar sector-specific policy has been recently suggested in the German Klimaschutzplan. Under such a decarbonization scheme, the model seeks to reduce the carbon-dioxide emissions by a certain percentage while investing in the cost-minimizing vehicle mix. In Scenarios II and IV, the national CO2-cap is replaced by a CO2 fleet target for new vehicle registrations (in g CO2/km). The binding measures, first introduced in 2012 by the European Commission, are integrated into the model (EC, 2017). In this case, the model can only invest in new vehicle capacities if the average emission levels do not exceed the fleet target. Unlike with the CO2-cap, only the "tank-to-wheel", or the emissions directly emitted from the vehicle, are relevant.

Whereas Scenarios I and II require the model to make investments in infrastructure for the deployment of new vehicle technologies, Scenarios III and IV present an alternative political framework. In these scenarios, it is

[10] Gas stations are assumed to be in operation 12 hours a day at 75% capacity with enough storage to cover demand for 6 days. The average driving distance for tanker transport for benzin and diesel is 80 km, for liquid hydrogen 300 km (Dodds et al., 2014a).

assumed that, e.g., the government will provide financial support for the infrastructure needed to decarbonize the road transport sector. Therefore, this cost factor is not included in the optimization and allows for technologies with little infrastructure today (such as FCEVs and BEVs) to be more competitive.

The decarbonization schemes are summarized in Table 3. Depending on the scenario, at least two of the given constraints will be included in the model simulation.

Decarbonization Scheme	**Measure**	**2020**	**2030**	**2050**
European CO_2-Cap (all sectors)	CO_2-eq reduction with respect to 1990	-20%	-40%	-80%
National CO_2-caps in road transport sector	CO_2-eq reduction with respect to 1990	-5%	-42%	-80%
Fleet target for new registrations (passenger vehicles)	g CO_2 / km	95	50	50
Fleet target for new registrations (light-duty vehicles)	g CO_2 / km	147	147	147

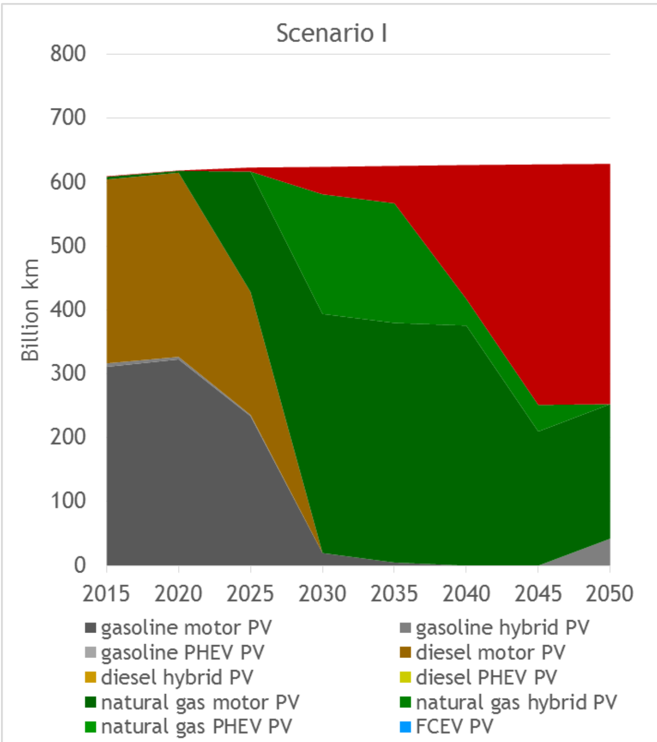
Table 3: Overview of Decarbonization Schemes Considered in the Scenarios[11]
Sources: ewi ER&S, EC (2017), BMUB (2016), UBA (2012)

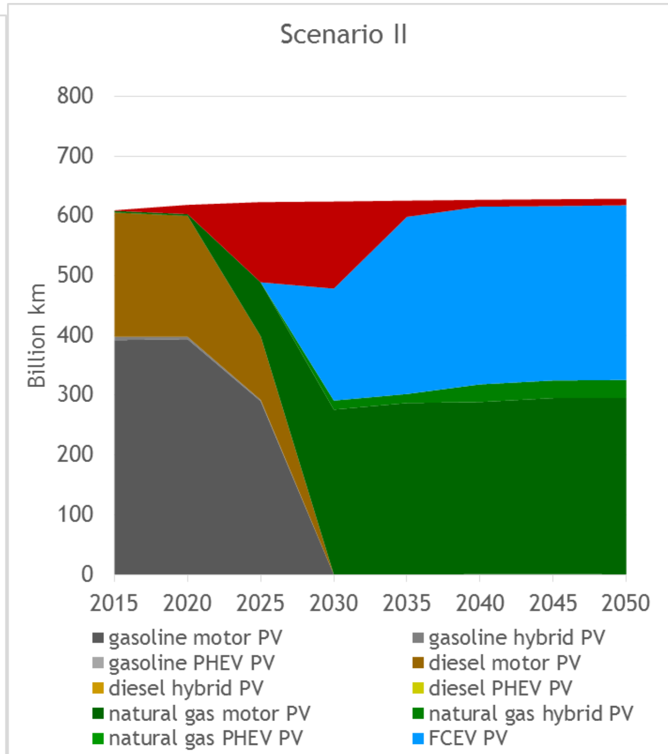
[11] Passenger vehicles as well as light-duty vehicles are currently required to meet strict fleet targets for 2020. It has been heavily discussed, as to whether the fleet targets should be extended. It is assumed in the analysis that the fleet target for passenger vehicles will be extended to 2030. LDVs, however, are assumed to no longer be forced to reach a fleet target. Neither PV nor LDV will become less efficient—therefore the fleet target remains constant from 2030 onwards.

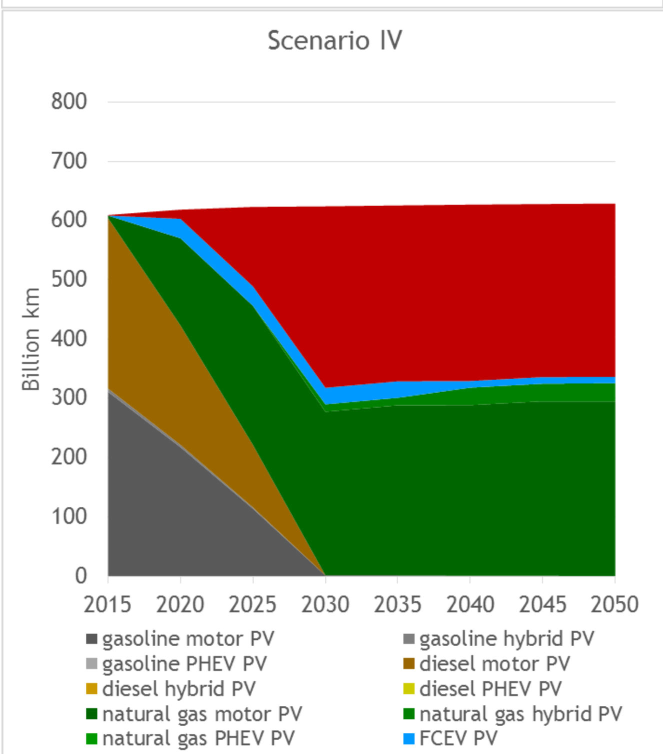
Scenario Results

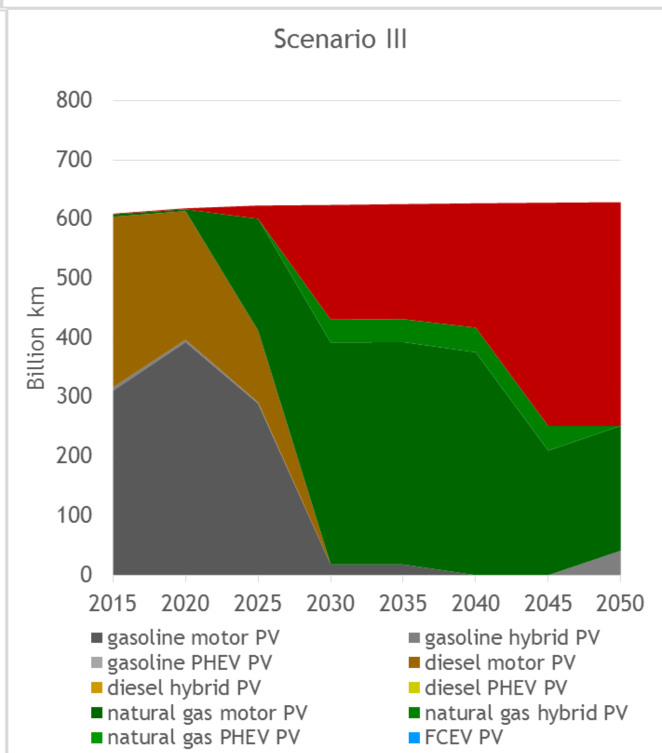
The results for the scenarios are summarized in the figures below.

Results for Passenger Vehicles in Germany



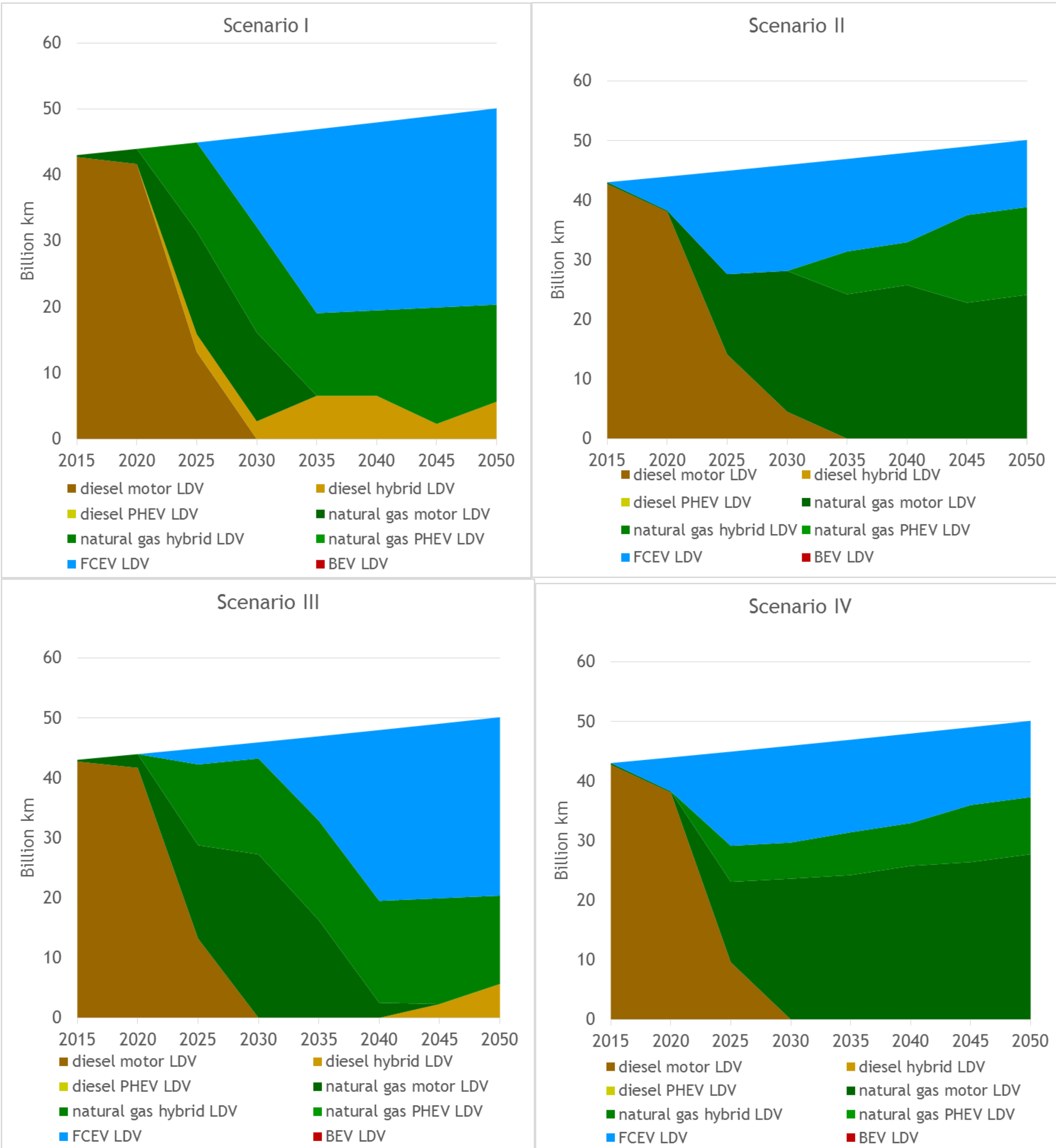






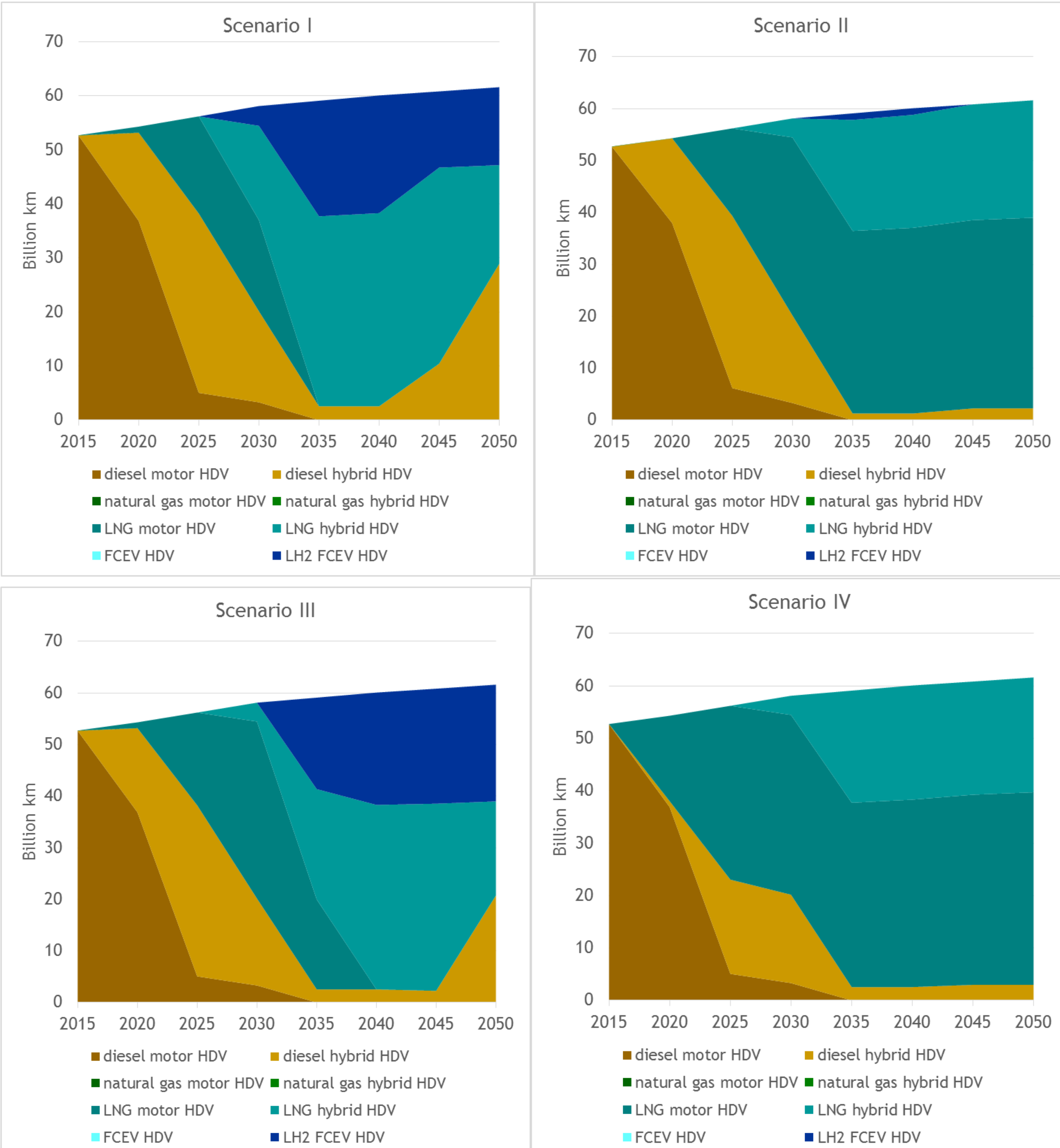
Figures 2-5: Scenario results for passenger vehicles in Germany up to 2050

Results for Light-Duty Vehicles in Germany



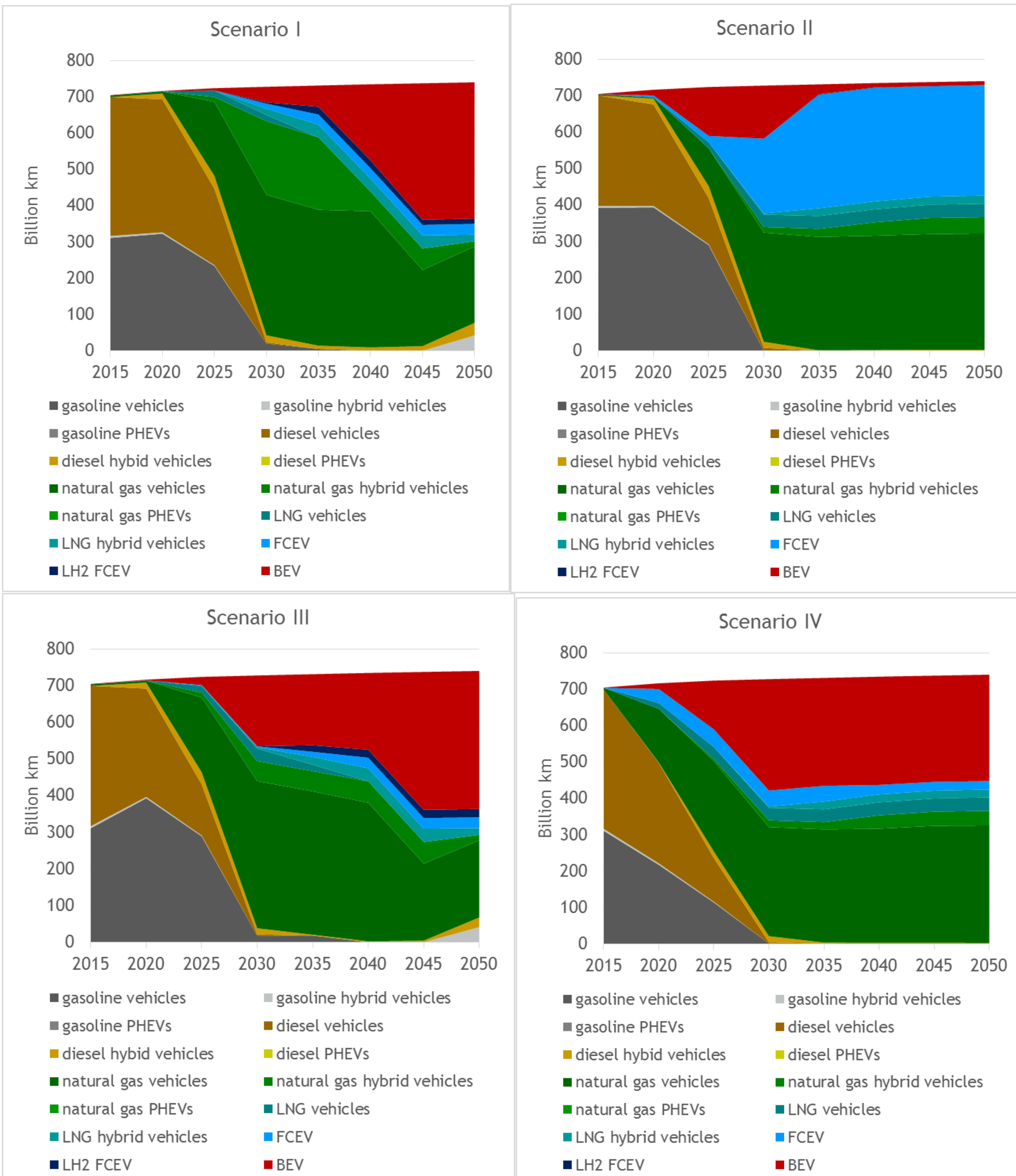
Figures 6-9: Scenario results for light-duty vehicles in Germany up to 2050

Results for Heavy-Duty Vehicles in Germany



Figures 10-13: Scenario results for heavy-duty vehicles in Germany up to 2050

Results for German Road Transport Sector



Figures 14-17: Scenario results for complete road transport sector in Germany up to 2050

Comparison CO_2 Emissions

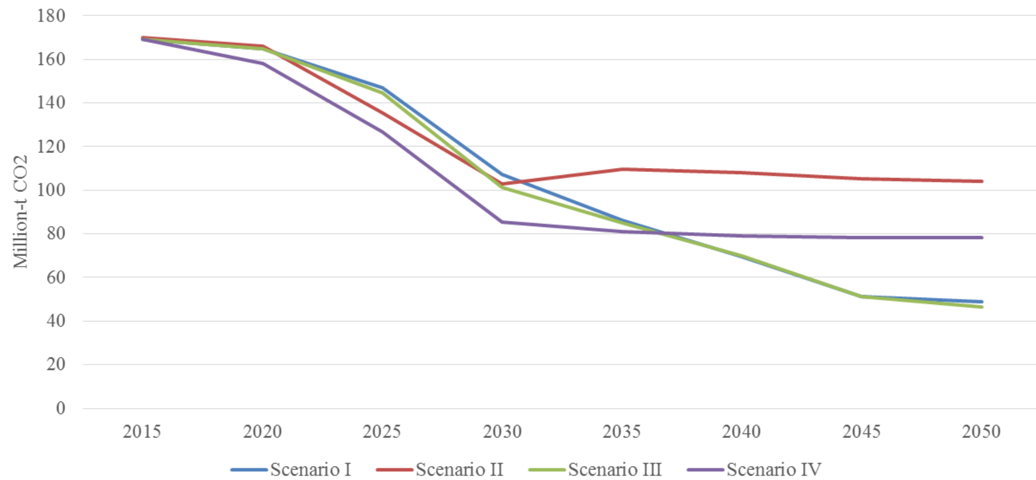


Figure 18: CO2-emissions emitted in road transport sector in Germany by Scenario

Conclusion

The European Union has set climate and energy targets to reduce greenhouse gas (GHG) emissions as well as increase the share of renewable energy generation (RES) in order to achieve a transformation to a long-term low-carbon economy. The study at hand examines multiple welfare-optimal pathways for decarbonizing the German road transport sector while taking into account European and German energy policies.

The results show that generation capacities will shift to favor renewable and gas generation, which eventually replace coal capacity in Germany. The decarbonization targets for the road transport sector trigger an increase in cost-optimal power to gas and power to fuel capacity that is capable of providing cross-sectoral flexibility and replacing conventional fuels. For passenger cars, gas engines and electric vehicles become increasingly important, while heavy-duty vehicles are mainly powered by liquefied hydrogen fuel cells or power-to-fuel diesel. Nevertheless, under a g CO2/km fleet target, almost twice as many CO2-emissions are emitted in the road transport sector in Germany in 2050. In addition, under both a fleet target and a CO2-cap, emissions are reduced in 2050 if infrastructure support is provided.

By constructing different pathways for the decarbonization of the road transport sector, we are able to compare politically-motivated pathways with a reference case. Such a comparison may be beneficial for researchers, professionals and policy makers alike.

References

Becker, W. L., Braun, R. J., Penev, M., and Melania, M. (2012). Production of Fischer - Tropsch liquid fuels from high temperature solid oxide co-electrolysis units. Energy, 47: 99-115.

BMWI (2010). Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Bundesministerium für Wirtschaft und Energie, Berlin.

BMUB (2016). Klimaschutzplan 2050: Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Berlin.

BNetzA (2016). Genehmigung des Szenariorahmens für die Netzentwicklungspläne Strom: 2017-2030. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, Bonn.

Dagoumas, A. S. and Barker, T. S. (2010). Pathways to a low-carbon economy for the UK with the macro-econometricE3MG model. Energy Policy, 38: 3067-3077.

dena (2015). Systemlösung Power to Gas. Chancen, Herausforderungen und Stellschrauben auf dem Weg zur Marktreife. Deutsche Energie-Agentur GmbH, Berlin.

DLR (2014). Power-to-Gas (PtG) im Verkehr: Aktueller Stand und Entwicklungsperspektiven. Deutsches Zentrum für Luft- und Raumfahrt e.V., Berlin.

Dodds, P. E. and McDowall, W. (2014a). Supporting Information: Methodologies for representing the road transport sector in energy system models. International Journal of Hydrogen Energy, 39(5): 2345-2358.

Dodds, P. E. and McDowall, W. (2014b). Methodologies for representing the road transport sector in energy system models. International Journal of Hydrogen Energy, 39: 2345-2358.

EC (2006). World Energy Technology Outlook - 2050: WETOH2. European Commission, Brussels.

EC (2010). EU energy trends to 2030: Update 2009. European Commission, Brussels.

EC (2013). EU Energy, Transport and GHG Emissions Trends 2050: Reference Scenario 2013. European Commission, Brussels.

EC (2016a). EU Reference Scenario 2016: Energy, transport and GHG emissions: Trends to 2050. European Commission, Brussels.

EC (2016b). Statistical Pocketbook 2016: EU Transport in Figures. European Commission, Brussels.

EC (2017). EU Climate Action Policy: Road Transport. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en. Accessed June 2017.

EC FCH JU (2010). A portfolio of power-trains for Europe: a fact-based analysis. Fuel Cells and Hydrogen Joint Undertaking. Brussels.

Edwards, R., Larivé, J.-F., Rickeard, D., and Weindorf, W. (2014). Summary of energy and GHG balance of individual pathways: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. JRC/CONCAWE/LBST, Brussels/Ottobrunn.

EEA (2015). Monitoring CO2 emissions from new passenger cars and vans in 2014. European Environment Agency, Copenhagen.

EIA (2015). Annual Energy Outlook 2015. U.S. Energy Information Administration, U.S. Department of Energy, Washington, DC.

Elsner, P. and Sauer, D. U. (2015). Energiespeicher: Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“. Fraunhofer-Institut für Chemische Technologie, Pfinztal.

EMISIA SA (2013). Transport data collection supporting the quantitative analysis of measures relating to transport and climate change. EMISIA SA, Thessaloniki.

ENTSO-E (2014). Statistical Factsheet 2013. European Network of Transmission System Operators for Electricity, Brussels.

ENTSO-E (2015a). Scenario Outlook & Adequacy Forecast

ENTSO-E (2015b). TYNDP 2016. Scenario Development Report. European Network of Transmission System Operators for Electricity, Brussels.

FCH (2010). The Role of Battery Electric Vehicles, Plug-in-Hybrids and Fuel Cell Electric Vehicles. Fuel Cells and Hydrogen Joint Undertaking, Brussels.

Fuchs, G., Lunz, B., Leuthold, M., and Uwe, D. (2012). Technologischer Überblick zur Speicherung von Elektrizität: Überblick zum Potenzial und zu Perspektiven des Einsatzes elektrischer Speichertechnologien. Institut für Stromrichtertechnik und Elektrische Antriebe, Aachen.

Fürsch, M., Hagspiel, S., Jägemann, C., Nagl, S., Lindenberger, D., Tröster; E. (2013). The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050. Applied Energy, 104: 642-652.

Growitsch, C., Hecking, H., John, C., Nick, S., and Schwind, H. (2013). Potenziale für Erdgas im Straßenverkehr – eine ökonomische Analyse. Energiewirtschaftliches Institut an der Universität zu Köln, Köln.

Gül, T., Kypreos, S., Turton, H., and Barreto, L. (2009). An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model (GMM). Energy, 34: 1423-1437.

ICCT (2015). European Vehicle Market Statistics: Pocketbook 2015/16. International Council on Clean Transportation, Wilmington.

IEA (2013). World Energy Outlook 2013. International Energy Agency, Paris.

IEA (2014). CO2 Emissions from Fuel Combustion: Highlights. International Energy Agency, Paris.

IEA (2015). World Energy Outlook 2015. International Energy Agency, Paris.

ifeu (2012). Aktualisierung ”Daten- und Rechenmodell: Energieverbrauch und Schadstoffemissionen des motorisierten Verkehrs in Deutschland 1960-

2030“ TREMOD. Heidelberg.

Jägemann, C., Fürsch, M., Hagspiel, S., and Nagl, S. (2013). Decarbonizing Europe's power sector by 2050 - Analyzing the economic implications of alternative decarbonization pathways. Energy Economics, 40: 622-636.

Joest, S., Fichtner, M., Wietschel, M., Bünger, U., Stiller, C., Schmidt, P., and Merten, F. (2009). „Woher kommt der Wasserstoff in Deutschland bis 2050?“, BMVBS, Berlin.

KBA (2015). 14.259 Kilometer: Die jährliche Fahrleistung deutscher Pkw. ‘‘https://www.kba.de/SharedDocs/Pressemitteilungen/DE/2015/pm_15_15_jaehrliche_fahrleistung_deutscher_pkw_pdf.html?nn=654808”, accessed 2017-06-30.

Kirsten, S. (2014). Renewable Energy Sources Act and Trading of Emission Certificates: A national and a supranational tool direct energy turnover to renewable electricity-supply in Germany. Energy Policy, 64: 302-312.

Kitous, A., Criqui, P., Bellevrat, E., and Château, B. (2010). Transformation Patterns of the Worldwide Energy System-Scenarios for the Century with the POLES Model. The Energy Journal, 31(1): 49-82.

Knaut, A., Tode, C., Lindenberger, D., Malischek, R., Paulus, S., and Wagner, J. (2016). The reference forecast of the German energy transition - An outlook on electricity markets. Energy Policy, 92: 477-491.

Maisonnier, G., Perrin, J., Trümper, C., and Steinberger-Wilckens, R. (2007). European Hydrogen Infrastructure Atlas and Industrial Excess Hydrogen Analysis: PART II: Industrial surplus hydrogen and markets production. IFP/AIR LIQUIDE/PLANET GbR, Paris/Oldenburg.

McDowall, W. and Dodds, P. (2012). A review of low-carbon vehicle and hydrogen end-use data for energy system models. UCL Energy Institute, London.

Oak Ridge National Laboratory (2011). Biomass Energy Data Book: Edition 4. Oak Ridge National Laboratory, Oak Ridge.

Özdemir, E. D. and Hartmann, N. (2012). Impact of electric range and fossil fuel price level on the economics of plug-in hybrid vehicles and greenhouse gas abatement costs. Energy Policy, 46: 185-192.

Pasaoglu, G., Honselaar, M., and Thiel, C. (2012). Potential vehicle fleet CO2 reductions and cost implications for various vehicle technology deployment scenarios in Europe. Energy Policy, 40: 404-421.

Pestana, R. (2015). e-HIGHWAY 2050. Modular Development Plan of the Pan-European Transmission System 2050. Redes Energéticas Nacionais, Lissabon.

Peters, D., Reith, M., and Weller, M. (2015). Nachhaltige Mobilität mit Erdgas und Biomethan: Marktentwicklung 2014/2015: Die Fortschritte im dritten Jahr nach der Unterzeichnung der Absichtserklärung. Deutsche Energie-Agentur GmbH, Berlin.

Rhenus Logistics (2007). LKW-Maut in Deutschland. Rhenus AG & Co. KG, Duisburg.

RTE (2015). Europe’s future secure and sustainable electricity infrastructure: e-Highway2050 project results. Réseau de transport d'électricité, La Défense.

Schaber, K., Steinke, F., and Hamacher, T. (2013). Managing Temporary Oversupply from Renewables Efficiently: Electricity Storage versus Energy Sector Coupling in Germany. International Energy Workshop, Paris.

Schlesinger, M., Lindenberger, D., and Lutz, C. (2014). Entwicklung der Energiemärkte - Energiereferenzprognose. Prognos/EWI/ GWS, Basel/Köln/Osnabrück.

Shell (2010). Shell LKW-Studie: Fakten, Trends und Perspektiven im Straßengüterverkehr bis 2030. Shell Deutschland Oil Gmbh, Hamburg.

Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., and Wilhelmsson, F. (2011). Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. Futures, 43: 1105-1116.

Spiecker, S. and Weber, C. (2014). The future of the European electricity system and the impact of fluctuating renewable energy - A scenario analysis. Energy Policy, 65: 185-197.

UBA (2012). Daten zum Verkehr: Ausgabe 2012. Umwelt Bundesamt, Dessau.

UBA (2013). Politikszenarien für den Klimaschutz VI: Treibhausgas-Emissionsszenarien bis zum Jahr 2030. Umwelt Bundesamt, Dessau.

UBA (2015). Umwelttrends in Deutschland: Daten zur Umwelt 2015. Umwelt Bundesamt, Dessau.

Van der Zwaan, B., Keppo, I., and Johnsson, F. (2013). How to decarbonize the transport sector? Energy Policy, 61: 562-573.

Vos Logistics (2014). Vos Logistics’ experience with LNG in road transport: a pioneer’s tale. Vos Logistics, Oss.

Wietschel, M. and Bünger, U. (2010). Verlgeich von Strom und Wasserstoff als CO2-freie Endenergieträger. Fraunhofer ISI/LBST, Karlsruhe/Ottobrunn.

Zachariadis, T. (2006). On the baseline evolution of automobile fuel economy in Europe. Energy Policy, 34: 1773-1785.