Renewables in Transport 2050

Empowering a sustainable mobility future with zero emission fuels from renewable electricity

Kraftstoffstudie II

Final Report

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RENEWABLES IN TRANSPORT 2050

EMPOWERING A SUSTAINABLE MOBILITY FUTURE WITH ZERO EMISSION FUELS FROM RENEWABLE ELECTRICITY
– EUROPE AND GERMANY –

AN EXPERTISE FOR THE
FVV – FORSCHUNGSVEREINIGUNG VERBRENNUNGSKRAFTMASCHINEN E.V.
(RESEARCH ASSOCIATION FOR COMBUSTION ENGINES)

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REPORT

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Disclaimer

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ACRONYMS AND ABBREVIATIONS

AEA	AEA consultants, now part of the Ricardo Group
bau	business-as-usual
BEV	Battery Electric Vehicle
BTL	Biomass-to-Liquid
CGH_2	Compressed Gaseous Hydrogen (Druckwasserstoff)
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CSP	Concentrating Solar Power
CTL	Coal-to-Liquid
eMob	Fuel/powertrain scenario in this study
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch
FVV	Forschungsvereinigung Verbrennungskraftmaschinen e.V. (engl.: Research Association for Combustion Engines) also: Fuel/powertrain scenario in this study
GHG	Greenhouse Gas
GT	Gas Turbine
GTL	Gas-to-Liquid
H_2	Hydrogen
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HIGH	Study scenario with high transportation demand
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
LBST	Ludwig-Bölkow-Systemtechnik
LCA	Life-Cycle Assessment
LDV	Light-duty vehicle
LH_2	Liquefied Hydrogen
LHV	Lower heating value
LNG	Liquefied Natural Gas
LOW	Study scenario with low transportation demand
MeOH	Methanol
MJ	Megajoule
Mtoe	Million tonnes oil-equivalents

N	Nitrogen
n. d. a.	no data available
NEDC	New European Driving Cycle
NG	Natural Gas
OHL	Overhead Lines, e.g. for trains
PHEV	Plug-in Hybrid Electric Vehicle
PJ	Petajoule (1000 PJ = 278 TWh)
pkm	person-kilometre
PM	Particulate Matter
$PtCH_4$	Power-to-Methane
PtG	Power-to-Gas
PtH_2	Power-to-Hydrogen
PtL	Power-to-Liquid
PTL	Fuel/powertrain scenario (this study)
PR	Progress Ratio
PV	Photovoltaic
REEV	Range Extender Electric Vehicle
SOEC	Solid Oxide Electrolyser (high temperature)
tkm	tonne-kilometre
TWh	Terawatthours (1000 TWh = 3600 PJ)
WtT	Well-to-Tank
WtW	Well-to-Wheel
yr	Year

EXECUTIVE SUMMARY

European and German greenhouse gas reduction targets of 80-95% by 2050 will require substantial contributions from the transport sector. As part of its main goal to reduce emissions of engines and turbines for the benefit of the economy, the environment, and society in general, the Research Association for Combustion Engines (FVV) has commissioned this study in order to develop, model, and assess scenarios assuming 100% renewable energy in transport by 2050. The analyses cover their feasibility as well as the resulting consequences for current developments and future use of combustion engines in transport. The study focuses on energy demands and greenhouse gas emissions, looking at fuels and their use 'well-to-tank' (i.e. excluding the combustion process itself). Three fuel and powertrain scenarios – one centred on synthetic fuels, another one on electric mobility, and a third one including a balanced mix of approaches – were defined and then modelled with two distinct transportation demand scenarios («HIGH», «LOW») for Germany and the EU-28.

Key **results** are:

- Growth in transportation demand (passenger-km, ton-km) is the strongest driver for fuel/electricity demand in all scenarios analysed. Efficiency improvements in combustion engines (including downsizing and mild hybridisation) could stabilise total fuel consumption.
- In the EU-28, almost all scenarios could technically be satisfied with domestic renewable electricity in the EU. However, in densely populated Germany all scenarios analysed would probably exceed the domestic technical or acceptable renewable electricity potentials.
- Depending on the scenario, total 2050 electricity demand (including for stationary use) could be by a factor of 1.1 to 3 higher than the total electricity demand in Germany today, and a factor 3 to 4.5 in the EU-28.
- Synthetic fuel (PtX) costs could halve between 2015 and 2050 in the EU including Germany. Further cost reductions are subject to project-specific business cases and parameters, most notably with regard to electricity price, annual full load hours, and CO_2 source. For cost-parity between PtL (excluding energy tax and VAT) with today's diesel price of 1.10 ct/$l_{\text{Diesel-equiv.}}$ (including taxes), renewable electricity costs in the order of 5 ct/kWh_e, CO_2 from a concentrated source (e.g. biogas upgrading), high temperature electrolysis, and 4000 annual equivalent full load hours are required.
- PtX costs are dominated by electricity costs and fuel specific plant efficiencies.
- PtX imports from world regions with favourable conditions for renewable electricity production are some 20% lower in costs. Imports are thus likely, particularly with increasing PtL volumes.

- Fuel distribution infrastructure costs are negligible compared to the upstream investments required for any of the scenarios analysed. However, while this holds true from a macro-economic perspective, initially low utilisation of new infrastructure will still provide for challenging short to mid-term business cases.
- Cumulated investments for 'Energiewende' (energy transition) in the transportation sector seem manageable for all scenarios analysed. On a linear annual break-down they are within the range of a low single-digit percentage point of annual GDP.

Key **conclusions and recommendations** that can be drawn from this study for achieving a robust sustainable development in mobility even at high transportation demands:

- Transport has to become more electric with regard to the fuel (electricity, PtX) and the embedding of combustion engines in propulsion systems (ICE hybrid, PHEV, REEV).
- Recent deployment rates of renewable power plants need to be sustained in Germany and deployment rate stepped-up in the EU-28 throughout the next decades.
- Energy (policy) scenarios necessarily need to account for increasing renewable electricity demands from the transportation sector as well as synergies from flexible PtX production for the integration of (fluctuating) renewable power sources.
- The massive investments needed for an energy transition in the transportation sector will require a risk-adequate investment security. International energy policies setting for robust long-term and intermediate targets with corresponding accountability could provide the necessary certainty to all actors in the fuel/vehicle value chain.

Fields that merit **further research** by FVV members and other institutions:

- Transportation demand scenarios/prognoses for passengers and goods are typically derived from GDP development assumptions; however, higher renewable fuel costs will in some way have repercussions on the transportation demand. Corresponding refined scenario analyses will help to better gauge possible development paths.
- This study focussed on energy, greenhouse gas emissions, costs, and investments. PtX fuels in combustion engines may in addition ease/reduce exhaust gas treatment needs. ICE design gains from combinations of synthetic fuels and combustion engines in different hybridisation concepts (PHEV, REEV) should be investigated to this end.
- PtX fuels offer a promising perspective for combustion engines. However, none of these fuels are fast-selling items in the foreseeable future. The analytical next step would thus be to assess pathways for the introduction of renewable fuels in practical terms, namely short to medium term opportunities for PtX cost reductions, development of blend fuel prices for conventional and renewable fuel mixes, and not least the regulatory framework that could facilitate the introduction of synthetic fuels.

1 INTRODUCTION

1.1 Study Background and Approach

Greenhouse gas reduction targets of 80-95% by 2050 will require substantial contributions from the transport sector. The Research Association for Combustion Engines (FVV) thus asked LBST to develop, model and assess whether 100% renewables in transport by 2050 are a pie in the sky, what the consequences are and about the determinants for the future use of combustion engines in transport. Figure 1 gives an overview of the approach taken in this study.

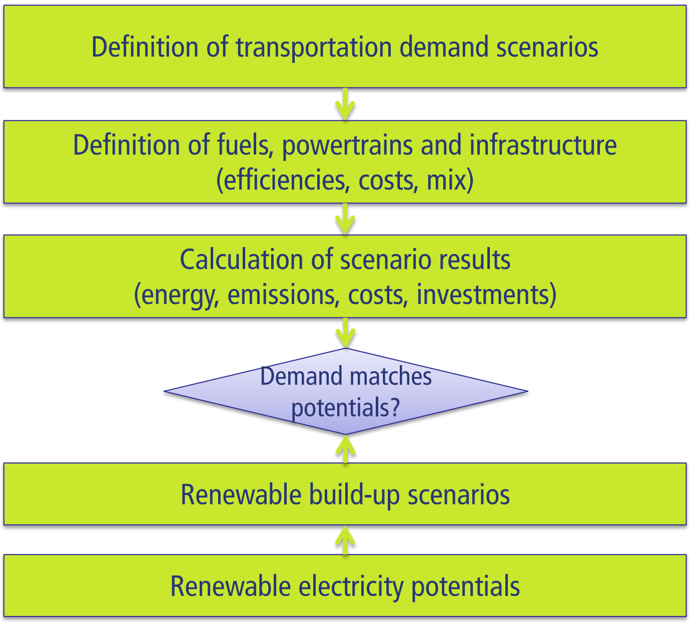

Figure 1: Study approach

First, greenhouse gas emission reduction targets have been discussed, also giving insights into recent developments of decarbonisation initiatives in the investment and financing sector (chapter 2). As can be seen from Figure 1 (bottom-up), technical potentials for the generation of renewable electricity have been assessed for Germany and EU-28 and built-up scenarios derived from this (chapter 3). Top-down from Figure 1, two distinct transportation demand scenarios (HIGH, LOW) were derived from literature for Germany and the EU-28 (chapter 4). Then, improvements in fuel supply pathways and fuel use have been discussed (chapter 5) and two distinct (PTL, eMob) and one mix fuel/powertrain scenario (FVV) defined (chapter 6). The resulting energy demands, greenhouse gas emissions and cumulated investments until 2050 were then calculated by the model for both Germany and the EU-28 (chapter 7). Finally, conclusions were drawn from this (chapter 8). Extensive details on input data and model results are annexed to this report.

1.2 Methodologies applied

a) Energy and emissions

The energy use and the emissions per energy unit are based on the lower heating value (LHV). Analogous [JEC 2014] for the calculation of the energy use and emissions of fuel supply pathways the energy requirement and associated emissions from the construction of fuel production facilities and vehicles are not taken into account.

b) Greenhouse gas emissions

Greenhouse gases considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)[1]. The global warming potential of the various greenhouse gases is expressed in CO_2 equivalents. Table 1 shows the global warming potential for a period of 100 years according to the Fourth and Fifth Assessment Reports (AR4 and AR5 respectively) of the Intergovernmental Panel on Climate Change (IPCC).

Table 1: Global warming potential (GWP) of various greenhouse gases [IPCC 2007], [IPCC 2013]

Greenhouse gas	IPCC Assessment Report 4 (g CO_2 equivalent/g)	IPCC Assessment Report 5 (g CO_2 equivalent/g)
CO_2	1	1
CH_4	25	30*
N_2O	298	265*

*Table 8.A.1 of the Fifth IPCC Assessment Report

Leading research institutions (e.g. Argonne National Laboratory for its tool 'GREET 2014') have already started to use the values of the latest (fifth) IPCC report, i.e. a GWP of 30 g/g for CH_4 and 265 g/g for N_2O [2] [IPCC 2013], which are used in the present study.

In the evaluation, only CO_2 generated by the combustion of fossil fuels is considered. The combustion of biomass is CO_2 neutral: the amount of CO_2 emitted during the combustion of biomass is the same as the amount of CO_2 which was taken from the atmosphere by the plants during their growth. Furthermore, climate impacts from high-altitude emissions of aviation have not been included in this study.

The energy requirements and greenhouse gas emissions resulting from the construction and decommissioning of manufacturing plants are not considered here. Furthermore,

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[1] Other greenhouse gases are CFCs, HFCs, and SF6, which are, however, not relevant in this context

[2] Without climate-carbon feedback (cc fb)

energy requirements and emissions resulting from the manufacturing and decommissioning of installations or applications (e.g. vehicles) consuming the hydrogen are not considered either.

c) **Energy use**

For the calculation of the energy requirements the so-called 'efficiency method' has been used similar to the procedure adopted by international organisations (IEA, EUROSTAT, ECE). In this method the efficiency of electricity generation from nuclear power is based on the heat released by nuclear fission which leads to an efficiency of about 33%. In the case of electricity generation from hydropower and other renewable energy sources that cannot be measured in terms of a calorific value (wind, solar energy) the energy input is assumed to be equivalent to the electricity generated which leads to an efficiency of 100%. The efficiency of geothermal electricity generation is set to 10%.

d) **Costs**

All costs have been calculated on a **full cost** basis and without taxes in order to gain a conservative, robust and level-playing field for cost comparison. An interest rate of 4% has been assumed for the calculation of the costs for capital. The depreciation period is assumed to be equal to the lifetime of the plant.

Specific investments have been calculated including technology-specific learning curves.

Cumulated investments up to the year 2050 comprise the cumulated investments 'well-to-tank', i.e. renewable power plants, electricity transport (where applicable), plants to produce power-to-anything (PtX), and fuel distribution infrastructure. Furthermore, cumulated investments include higher specific costs in the beginning as the 1st plant is more expensive than the nth plant.

2 LONG-TERM EMISSION REDUCTION TARGETS

2.1 Recent trends worldwide

The International Energy Agency started the executive summary of its World Energy Outlook 2008 as follows:

> *'The world's energy system is at a crossroads. Current global trends in energy supply and consumption are patently unsustainable — environmentally, economically, socially. But that can — and must — be altered; there's still time to change the road we're on.'*

This warning by the IEA was based on the observation that energy consumption and CO_2-emission patterns at world level are at contradicting pathways, the required reduction target was not mirrored by the real development: Energy consumption and CO_2-emissions at world level were still rising, year over year, while climate policy goals require severe CO_2-emission reductions until 2050.

Meanwhile, in 2015, it seems that the requirements of climate policy and economic interests are coming a bit closer: In 2014 for the first time, net-investments in renewable energy technologies (excluding large hydro) exceeded those in fossil fuel power plants at world level, while total investments (including those new fossil power plants which replace decommissioned plants) were almost comparable [Bloomberg 2015].

The collapse of oil prices by about 50% in autumn 2014 still holds on. At present, each of the primary fossil fuels (coal, oil and natural gas) is negotiated at price levels far below the past few years. Though this price weakness also might initiate higher fuel consumption, it already started to influence the mind setting of investors and politicians at least partly bringing their financial long-term decisions closer in line with climate policy-goals. The analysis of 459 divesting institutions indicates that in recent years about 2,600 billion USD are already divested from fossil fuel companies [gff 2015]. Some recent political and investor signals are:

- In recent months, the World Bank lead an initiative with 73 national governments, 11 regional governments, and more than 1,000 businesses and investors to build support for a global price on carbon emissions during the United Nations climate summit in New York. This inspired the governor of the Bank of England in October 2014, to reiterate its warning that climate change had to be seen as risk factor for investments into fossil fuels once political regulations with restriction to fossil fuel use create stranded invests [Shankleman 2014].

- Chinese policy started to seriously address air quality problems. For instance, by end of 2016 Beijing plans substitute the last coal fired power plant with power from cleaner sources [Mc Donell 2015].
- The Norwegian Government Pension Fund Global with a market value of more than 700 billion € in 2014 removed 32 coal mining companies from its portfolio. This act was seen as measure to reduce the risk facing from regulatory action on climate change [Carrington 2015].
- In May 2015 the 'IEA World Energy Outlook Special Report: Energy and Climate Change' envisages the peak of GHG emissions from the combustion of fossil fuels before 2020 in order to match the 2 degree goal [IEA 2015].
- In June 2015 the G-7 group committed at their meeting in Elmau in Bavaria to take 'urgent and concrete action' on climate change in 2015. The concrete action addressed [Freedman 2015]:
    - To develop a new climate agreement during the Paris Climate Summit in December 2015,
    - To take strong steps to ensure that global warming remains under the 2°C-target until 2050,
    - To commit cutting greenhouse gases by 40-70% until 2050 compared to 2010 levels, and
    - To decarbonize their economies by the end of the century.
- On 19th October 2015, the city of Oslo announced to divest its pension fund of about € 8 billion from coal, oil and gas companies. If so, this would be the world's first capital city action to ban investments into fossil fuels [gff 2015a].

Such developments probably might have an impact on the discussions at the Paris Climate Summit in December 2015 to negotiate for a worldwide action plan of decarbonisation with more stringent targets for the individual world regions.

Figure 2 shows the development of past GHG-emissions at world level with various projections until 2050. The blue dotted line gives the trend extrapolation in a business-as-usual scenario (BAU). The grey and green shaded areas reflect the range of uncertainty of allowed emissions in order to keep the resulting temperature increase in the range of 2-3°C. The green line shows the historical development of CO_2-emissions, which have a share of 60-65% on total GHG-emissions.

Finally, the lower grey line shows the historical development of CO_2-Emissions from the transport sector with extrapolation by 2050 in the business-as-usual scenario. It becomes obvious that a policy target of below 2°C by 2050 requires an individual target and accompanying measures also for the transport sector in order to reduce its impact below the anticipated development as seen in the BAU-scenario.

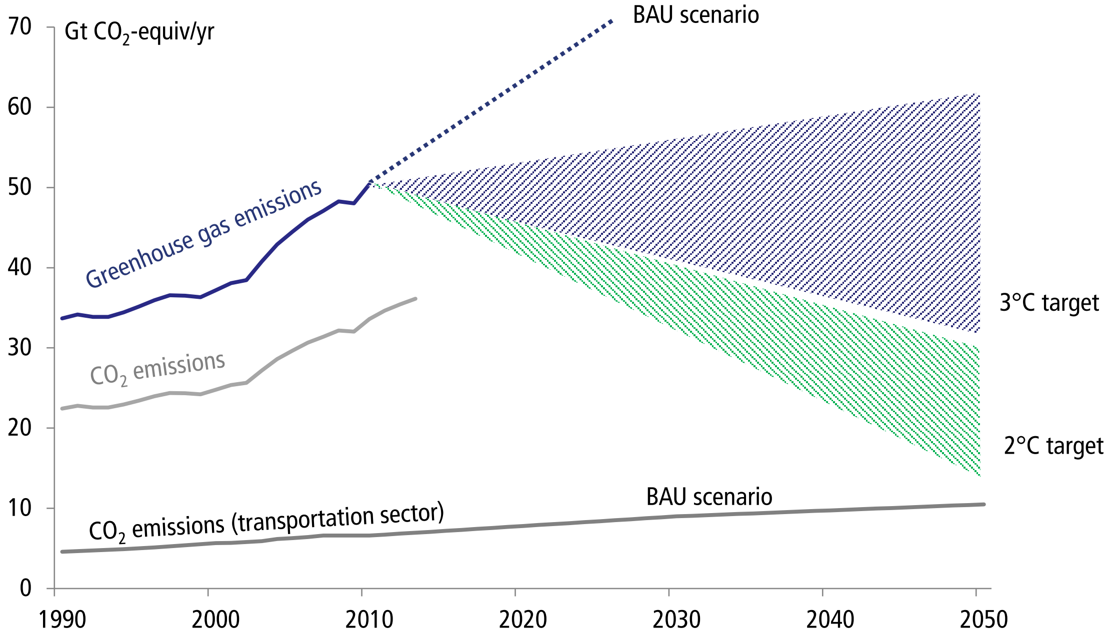


Figure 2: **Greenhouse gas emission scenarios at world level (LBST based on [IPCC 2013])**

2.2 USA/California

Since decades, for California as a leading car market the Air Resources Board (ARB) set emission and fuel standards for car companies aimed to reduce fuel consumption and emissions [CARB 2015]. In the present context the most relevant order is the California Executive Order B-16-2012, which was set into action on 23rd March 2012. It states [Brown 2012]:

> *'IT IS FURTHER ORDERED that California target for 2050 a reduction of greenhouse gas emissions from the transportation sector equalling 80 percent less than 1990 levels'. Intermediate targets in this order are:*
>
> *'... at least 10 percent of fleet purchases of light-duty vehicles be zero-emission by 2015';*
>
> *'... at least 25 percent of fleet purchases of light-duty vehicles be zero-emission by 2020';*
>
> *'Over 1.5 million zero-emission vehicles' by 2025.*

However, no details are given whether a 'well-to-tank' or 'well-to-wheel' scope is applied.

2.3 Europe

On 22 January 2014 the European Commission set the targets to reduce CO_2-emissions until 2030 by 40% compared to 1990 and reach a renewable energy share of 27% in final energy consumption [Ecofys 2014].

On 6th of March 2015 the ministers for environment of the EU member reiterated the target and decided an EU negotiating mandate for COP/Paris to reduce the CO_2 emissions by 40% until 2030 based on 1990 emission levels.

With regard to the GHG regulatory framework post-2020, the following sector targets are currently being discussed at the European stage, see Table 2.

Table 2: EU indicative targets for greenhouse gas emission reductions (base year 1990) based on different carbon reduction scenarios [EC-CLIMA 2015]

Sectors	2005	2030	2050
Power (CO_2)	-7%	-54 to -68%	-93 to -99%
Industry (CO_2)	-20%	-34 to -40%	-83 to -87%
Transport (incl. CO_2 aviation, excl. maritime)	+30%	+20 to -9%	-54 to -67%
Residential and services (CO_2)	-12%	-37 to -53%	-88 to-91%
Agriculture (Non-CO_2)	-20%	-36 to -37%	-42 to -49%
Other Non-CO_2 emissions	-30%	-72 to -73%	-70 to -78%
Total	**-7%**	**-40 to -44%**	**-79 to -82%**

The EC-White Paper 'Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system' discusses the following specific targets for the transport sector [EC 2011], always with respect to 2005:

- reduction of CO_2-emissions from bunker fuels for ships at least by 40% until 2050,
- the transport volume of vehicles with conventional combustion engine in cities should be reduced by 50% until 2030 and by 100% until 2050,
- inner city logistics should become CO_2-free until 2030,
- the major part of passenger transport within medium distances should be performed by rail,
- the volume of freight transport up to 300 km should be shifted to rail by 30% until 2030 and by 50% until 2050,
- the share of low-carbon fuels for aircraft should be increased by 40% until 2050,
- all major airports should be integrated into the (high-speed) rail network until 2050, and

- all harbours for sea vessels should be connected to the freight rail grid and, when possible, to inland water ways by 2050.

Specific targets for vans are formulated in regulation (EU) No. 510/2011:

- the fleet average of newly registered vans should not exceed specific CO_2-emissions of 175 g/km by 2017 and of 147 g/km by 2020. In reg. No. 253 (2014) these figures are adapted to different vehicle masses according to CO2= 147 g/km+0.096*(vehicle mass – $M_{average}$). $M_{average}$ is the average mass of new vehicles, registered within the last three years [EC 2014].

In 2014 the average van sold in Europe emitted 169.2 g/km, which is already below the 2017-target, according to provisional data from the European Environment Agency (http://www.eea.europa.eu/highlights/new-vans-sold-in-europe).

For passenger cars the regulation (EU) No. 333/2014 holds which requires that:

- the fleet average of newly registered passenger cars should not exceed specific CO_2-emissions of 130 g/km by 2015 and of 95 g/km by 2021.

In 2014, the passenger car fleet emissions averaged at 123.4 g/km, according to provisional data from the European Environment Agency (http://www.eea.europa.eu/data-and-maps/data/co2-cars-emission-8). Electric vehicle sales including hybrid cars amounted 67,000 in 2014, resp. 0.5% all new cars.

Figure 3 sketches the GHG-emissions of EU-27 between 1990 and 2008 (blue line) as well as the reduction targets until 2050. The light and dark blue areas indicate the reduction required to meet a 2°- and a 3°-target. The 2°-target requires the GHG-emission reduction of between 80 to 95%. The red line shows the GHG-emissions attributable to the EU-27 transport sector between 1990 and 2008. The dotted and broken red lines show the extrapolation according to two different emission scenarios, which more or less sketch the range of business-as-usual extrapolation of the trends with minor modifications.

Such a development would only be compatible with the EU-GHG-reduction target of 2°C, when all other sectors would reduce total GHG emissions to zero. The Target emissions for the whole EU-27 society would be already emitted from the transport sector alone.

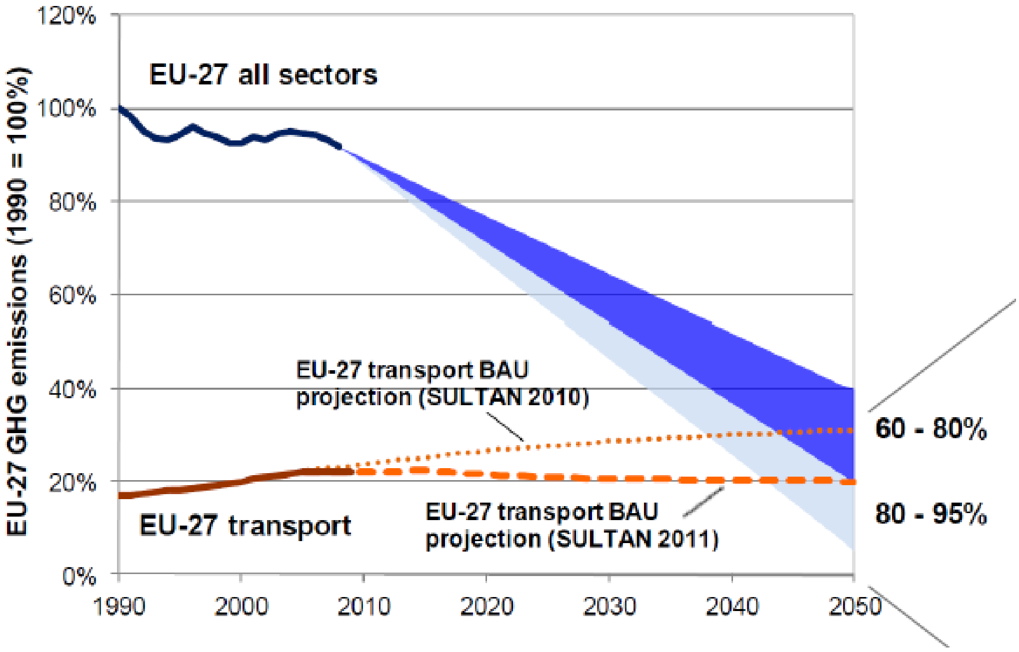


Figure 3: EU greenhouse gas emission scenarios [AEA et al. 2012]

Figure 4 exhibits the greenhouse gas emissions of the EU-27 transport sector. The aforementioned bau-scenarios are also represented with the dotted and broken red lines. In addition, a range of further GHG reductions is shown which would require further political restrictions and technological actions.

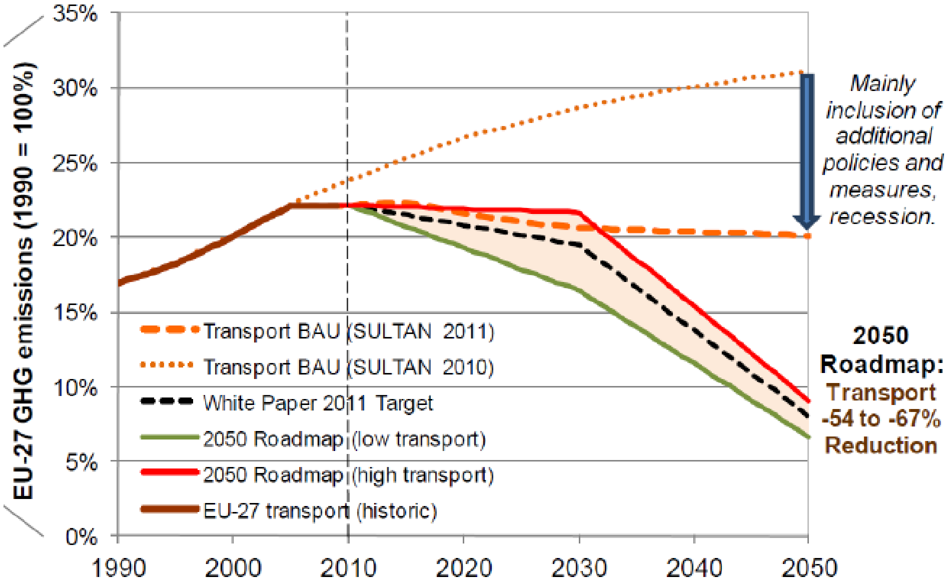


Figure 4: EU greenhouse gas emission scenarios compatible with GHG targets until 2050 [AEA et al. 2012]

2.4 Germany

As part of the European Union, Germany has the same specific CO_2-reduction targets as specified above in the regulations (EU) No. 510/2011 respectively its amendment (EU) No. 253/2014 for vans and regulation (EU) No. 333/2014 for cars.

In addition the energy concept of the present German government gives the following targets for the whole transport sector:

- Final energy consumption of transport sector should be reduced by 10% until 2020, and by 40% until 2050, always against 2005.
- In 2020 about 1 million electric vehicles should be registered in Germany. Until 2030 the total number of registered electric vehicles should increase to 6 million vehicles.

With regards to electricity, the Federal German Renewable Energy Law (EEG 2012) stipulates the following targets:

2020: 35%

2030: 50%

2040: 65%

2050: 80%

However, there are actors in the transport sector actively aiming for 100% renewable electricity for transport by 2050, such as the German railway operator Deutsche Bahn as stipulated in its Sustainability Report 2012 [DB 2012, p. 16].

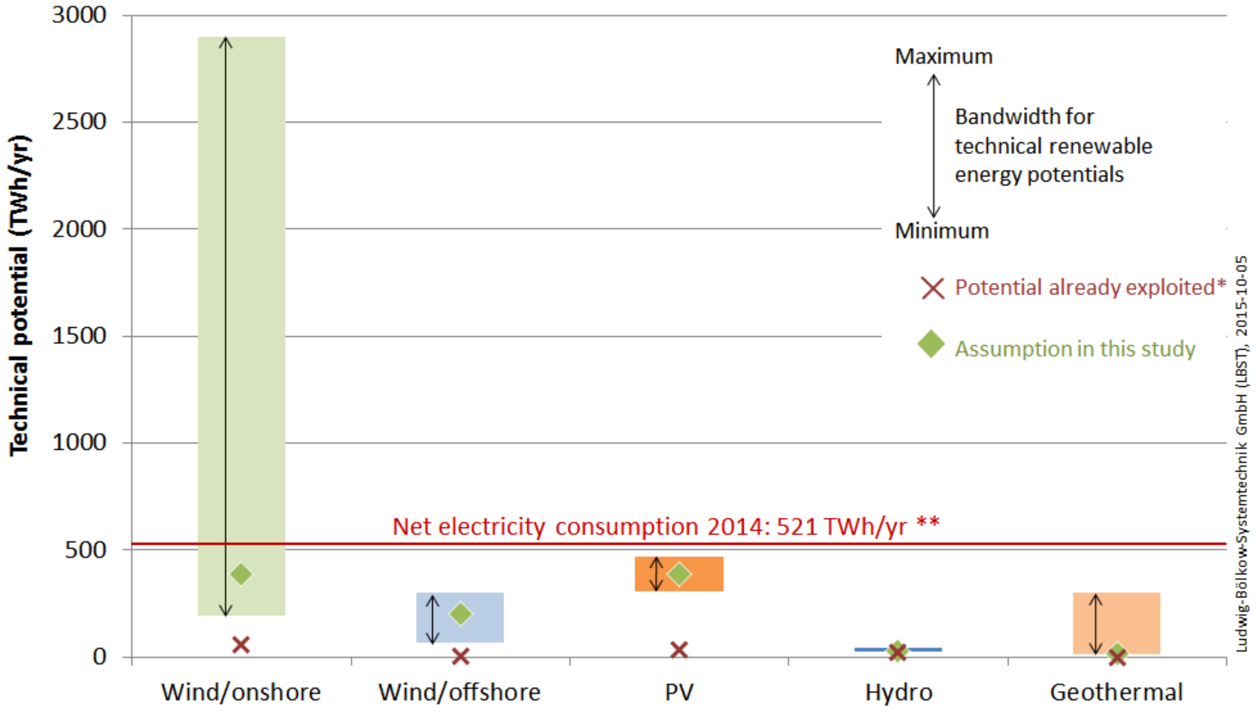
3 RENEWABLE POWER SUPPLY

For the purpose of comparing the electricity demands that result from the different transportation scenarios and its cost, first the technical renewable electricity production potentials had been determined for Germany and the EU-28 (chapter 3.1), then synthetic deployment curves have been applied to them (chapter 3.2).

3.1 Technical renewable electricity potentials

3.1.1 Germany

The basic approach and key literature/data sources for the assessment of renewable power resources in Germany are described in [MKS 2015]. For the purpose of this study, newly released literature has been assessed. A few data assumptions were slightly modified, however, without change in overall results. The technical production potential from renewable electricity sources in Germany is depicted in Figure 5.



Data: [BMU 2010], [BMU 2012], [BWE 2013], [ISE 2015], [IWES_PV 2012], [IWES 2012], [Quaschning 2013], [TAB 2003], [UBA 2013];
*Data for 2014: provisionally 08/2015 [AGEB 2015]; **Data for 2014: provisionally 08/2015 [BDEW 2015]

Figure 5: Renewable electricity potentials and current uses in Germany, depicted by source

As can be derived from the above-captioned Figure 5, there are significant technical renewable electricity potentials in Germany, mainly from wind onshore, wind offshore and photovoltaics[3]. Considering conservative assumptions result in an overall renewable electricity potential of 1,000 TWh_e per year in Germany. Assuming more progressive installation density and yield parameters result in renewable electricity supply potentials of some 4,000 TWh_e per year in Germany. For comparison, in 2014 the net electricity consumption in Germany was 521 TWh_e [BDEW 2015]. The renewable electricity potentials thus exceed current electricity consumptions by a factor of 2 to 7.

For this study, an average technical renewable electricity potential of 1,000 TWh_e/a is assumed for Germany. As per today, only some 11% of this renewable electricity potential has already been exploited in Germany.

3.1.2 EU

For the assessment of technical renewable electricity production potentials in Europe, a literature meta study has been performed and complemented with own calculations by the study authors where assumptions were lacking. The following renewable electricity sources have been assessed and are characterized in the following sub-chapters: Wind onshore, wind offshore, photovoltaics (PV), hydro power and geothermal power.

Wind power

There is now 128.8 GW of installed wind energy capacity in the EU (end 2014). These wind power capacity would, in an average wind year, produce some 284 TWh_e of electricity, which is enough to cover 10.2% of the EU's electricity consumption [EWEA 2014].

Wind offshore

Around 8,045 MW of offshore wind turbines are already installed throughout Europe The average offshore wind turbine size is 3.7 MW. The average water depth of wind farms is 22.4 m and the average distance to shore is 32.9 km [EWEA 2015]. Likely the size of installed turbines, average water depths and distances will increase over time because easily accessible areas with high production potentials are typically exploited first and technology progresses likewise. According to the European Wind Energy Association (EWEA), up to 66 GW_e offshore power plants might be installed in 2030 [EWEA 2015a].

According to [Matthies et al. 1995], the technical potential from offshore wind power in Europe is 3,028 TWh_e per year. A maximum water depth of 40 m and a maximum distance to shore of 30 km was assumed to this end. Meanwhile locations with significantly larger

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[3] There are further potentials from geothermal heat sources in Germany, however, these potentials would require ‘hydraulic fracturing’ for their exploration. To date, there is no public acceptance for this process in Germany. As a conservative approach, the lower boundary of geothermal electricity potentials has been considered here.

distances from coast are considered as realistic for the installation of offshore wind farms, especially offshore the coast of Germany. On the other hand, especially in Germany only a few of the approved offshore wind farms are closer than 12 nautical miles (22 km) offshore the coast. In UK the wind farms are generally the distance from the cost is lower than in Germany.

[IWES 2012] analysed the technical potential of offshore renewable energy resources of selected European countries. They concluded that some 70% of the offshore wind power potential (8,100 TWh/a from 11,197 TWh/a) can be found in water depth > 50 m, especially along the Atlantic coastlines oriented to the West, i.e. UK, Ireland, Spain and Portugal, as well as the northern parts of the North Sea (Norway, UK). However, for water depths of > 50 m floating structures are required which are still in the early stage of research and development. Therefore, only water depth ≤ 50 m has been taken into account in this study.

For the lower limit the values indicated in [IWES 2012] for a water depth of ≤ 50 has been used for the calculation except for Belgium, Germany, and Greece. For Belgium and Greece the value indicated in [Matthies et al. 1995] and for Germany the value indicated in [Viertel et al 2005] has been used. The upper values have been derived from [IWES 2012] except for Belgium, Denmark, France, Greece, Ireland, Portugal, Spain, and UK where the values indicated in [Matthies et al. 1995] has been used. All in all, some 2,132 to 3,735 TWh_e of electricity per year of electricity may be available as technical offshore wind potentials of EU Member States at a water depth of maximum 50 m. Offshore wind power potentials in Europe exceed current European electricity demands.

<u>Wind onshore</u>

Estimations for onshore wind power generation potentials are based on the following (conservative) assumptions:

- Installed nominal power of wind power plant: 3 MW
- Rotor diameter: 115 m
- Distance between wind power plants: 4 rotor diameters [IWES 2013]
- Equivalent full load period is 2,000 to 3,700 h/yr, depending to the EU Member State.

Furthermore, for the EU member states other than Germany the following assumptions have been applied for onshore wind power:

  - The upper boundary is similar to the actual wind power plant density in the German state of Schleswig-Holstein as of today, i.e. 2.3% of the area (including plant spacing applying a distance of 4 rotor diameter between the wind power plants). 4336 MW of rated wind power capacity has been installed end 2014 in Saxony-Anhalt. The land area of Saxony-Anhalt amounts to 20,446 km^2 which leads to about 0.21 MW per km^2 of land area.

- Lower boundary is similar to the actual wind power plant density in the German state of Sachsen-Anhalt, i.e. 1.5% of the area (including plant spacing applying a distance of 4 rotor diameter between the wind power plants). 5090 MW of rated wind power capacity has been installed end 2014 in Schleswig-Holstein. The land area of Schleswig-Holstein amounts to 15,731 km² which leads to about 0,32 MW per km² of land area.

In case of Germany the potential indicated in [IWES 2013] has been used where 2% of land area excluding an outside protection perimeter of 1000 m to e.g. nearby buildings (including the protection perimeter would be equivalent to a land use density of some 4% of the land area) has been occupied with wind power plants. According to [IWES 2013] about 194,000 MW could be installed in Germany. The land area of Germany amounts to 356,968 km² leading to about 0,54 MW per km² of land area.

The assumptions described above lead to the technical potential for electricity from onshore wind power in the EU shown Table 3.

Table 3: Technical potential for electricity from onshore wind power

State	Rated capacity		Equivalent full load period		Electricity generation potential	
	min (MW)	max (MW)	min (h/yr)	max (h/yr)	min (TWh/yr)	max (TWh/yr)
Austria	17,548	26,769	2,150	2,150	37.7	57.6
Belgium	6,411	9,781	2,309	2,309	14.8	22.6
Bulgaria	23,523	35,884	3,077	3,077	72.4	110.4
Croatia	11,965	18,252	2,703	2,703	32.3	49.3
Cyprus	1,960	2,989	2,731	2,731	5.4	8.2
Czech Republic	16,389	25,002	2,022	2,022	33.1	50.5
Denmark	8,991	13,716	2,260	2,260	20.3	31.0
Estonia	9,165	13,980	1,977	1,977	18.1	27.6
Finland	64,787	98,831	3,696	3,696	239.4	365.2
France	115,723	176,532	2,435	2,435	281.8	429.8
Germany	194,431	194,431	2,028	2,028	394.3	394.3
Greece	27,741	42,319	1,957	1,957	54.3	82.8
Hungary	19,584	29,875	2,200	2,200	43.1	65.7
Ireland	14,611	22,289	2,667	2,667	39.0	59.4
Italy	62,359	95,127	2,172	2,172	135.4	206.6
Latvia	13,699	20,897	2,460	2,102	33.7	43.9
Lithuania	13,828	21,095	3,504	3,504	48.5	73.9
Luxemburg	548	837	1,991	1,991	1.1	1.7
Malta	67	102	2,533	2,533	0.2	0.3
Netherlands	7,188	10,964	3,100	3,478	22.3	38.1
Poland	64,574	98,506	1,978	3,600	127.7	354.6
Portugal	19,502	29,750	2,544	2,544	49.6	75.7
Romania	50,371	76,840	2,932	2,932	147.7	225.3
Slovakia	10,350	15,789	2,000	2,000	20.7	31.6
Slovenia	4,295	6,553	2,000	2,000	8.6	13.1
Spain	105,948	161,621	2,238	2,238	237.1	361.7
Sweden	87,155	132,953	2,826	2,826	246.3	375.7
UK	51,239	78,163	2,506	2,506	128.4	195.9
Total EU 28	1,023,953	1,459,845			2,493	3,753

All in all, the technical potential from onshore wind in Europe is some 2,493 to 3,753 TWh_e per year.

Solar power

Photovoltaics (PV)

For photovoltaics, there are a couple of parameters that are highly sensitive to the result.

The methodological approach as described by [Quaschning 2000] is used for the calculation of the technical PV production potentials in the EU.

The roof area of residential buildings has been derived from the dwelling area per capita. The dwelling area in Germany has been derived from [DESTATIS 2012]. The average dwelling area from the other EU states has been estimated using an approach described in [BIOCLIMECO 2002]. According to [BIOCLIMECO 2002] there is a relationship between the dwelling area per capita and the gross domestic product (GDP) per capita. In case of developed countries the relationship is:

$$A = 0.981 \cdot x^{0.3581}$$

where

A = dwelling area per capita in [m^2]

x = gross domestic product (GDP) per capita in [US$/cap] (purchasing power parity)

The dwelling area per capita has been multiplied with the population in the different countries. For the conversion of the dwelling area to the roof area a factor of 0.8 as indicated in [Quaschning 2000] has been used (i.e. the roof area is 80% of the dwelling area).

For the estimate of the roof area of non-residential buildings the specific roof area of non-residential buildings per capita in Germany indicated in [Quaschning 2000] is used as basis for the calculation. It is assumed that the area of non-residential buildings is proportional to the gross domestic product (a higher gross domestic product leads to more office and industrial buildings and as a result to a higher roof area).

Because of shading and other constraints it is assumed that 40% of the roof area is not suitable for photovoltaic installations. It is also assumed that the photovoltaic modules cover only 50% of the total area suitable for photovoltaics. As a consequence the theoretical potential photovoltaic area amounts to about 30% of the total roof area. For the technical potential of renewable electricity production from photovoltaics, predominantly rooftop PV is considered. 2/3rd of suitable rooftop areas are allocated for PV use; the remaining 1/3rd of suitable rooftop areas is taken aside for potential use by solar heat installation.

For the calculation of the electricity potential the different irradiation values in the different countries are used. Also the deviation of the inclination from the optimum inclination is accounted for by applying factors as described in [Quaschning 2000]. An additional factor is applied to consider shading and fouling. Table 4 shows the reduction factors for the calculation of the potentials for electricity from roof-mounted photovoltaic power plants.

Table 4: **Reduction factors for the calculation of the energy potentials of photovoltaics**

Class	Share	Azimuth-angle	Inclination	Losses from		Total losses (average)
				Inclination (average)	Shading and fouling	
I	25% of sloped roof*	up to +/-45°	up to 60°	10%	5%	15%
	50% of flat roof*	0°	30°	0%	10%	10%
II	75% of sloped roof*	+/-90°	up to 60°	15%	5%	20%
	50% of flat roof*	0°	30°	0%	10%	10%

*adequate for solar energy (30% of total roof area)

In case of sloped roofs adequate for photovoltaic installations 25% (7.5% of sloped roofs total) meet the requirements for class I and 75% (22.5% of sloped roofs total) meet the requirements for class II.

50% of the flat roofs adequate for photovoltaic installations (15% of flat roofs total) are class I roofs and 50% of the flat roofs adequate for photovoltaic installations (15% of flat roofs total) are class II roofs. The share of sloped roofs has been assumed to be 69%, the share of flat roofs 31%.

The efficiency of photovoltaic panels based on silicon photovoltaic cells ranges between 14 and 20%. Furthermore losses from DC/AC converters and cables (balance of plant) have to be taken into account which has been assumed to be between 5 and 11% leading to an efficiency of 89 to 95%[4]. Table 5 show the bandwidth of the efficiency of the photovoltaic power plants assumed in this study.

Table 5: **Efficiency photovoltaic power plant**

	min	max
Efficiency (PV panel)	14.0%	20.0%
DC/AC converter, cables	89.0%	95.0%
Total	12.5%	19.0%

The assumptions described above lead to the technical potential for electricity from roof-mounted photovoltaic power stations shown in Table 6.

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[4] This must not be mixed up with the 'Performance Ratio' (PR) which includes losses from shading, fouling and deviation from optimal inclination. The inclusion of the losses from shading, fouling and deviation from optimal inclination assumed in this study lead to a PR of 0.75 and 0.80 which is typical for PV power plants today.

Table 6: Technical potential for electricity from roof-mounted photovoltaic power stations

State	Irradiation (kWh/(m²*yr)	Roof area* (km²)	PV potential min (TWh/yr)	PV potential max (TWh/yr)
Austria	1200	154	13	19
Belgium	1000	189	13	20
Bulgaria	1400	70	7	10
Croatia	1400	50	5	7
Cyprus	1800	12	2	2
Czech Republic	1000	145	10	15
Denmark	1000	97	7	10
Estonia	1000	16	1	2
Finland	900	90	6	9
France	1300	1069	96	146
Germany	1200	1422	118	180
Greece	1500	169	18	27
Hungary	1200	118	10	15
Ireland	1000	81	6	9
Italy	1400	924	89	136
Latvia	1000	23	2	2
Lithuania	1000	36	3	4
Luxemburg	1000	15	1	2
Malta	1800	6	1	1
Netherlands	1000	312	22	33
Poland	1200	450	37	57
Portugal	1800	141	18	27
Romania	1500	196	20	31
Slovakia	1200	70	6	9
Slovenia	1300	30	3	4
Spain	1600	709	78	120
Sweden	1000	167	12	18
UK	1000	1061	73	112
Total EU 28		7,823	673	1,026

*adequate for solar energy (30% of total roof area)

PV on green or brown fields is considered to a small extend only, which reflects the notion of the regulatory framework in place, namely the renewable feed-in law (EEG). Here, PV on building facades and along motor highways and railroad tracks are included. However, there is an additional potential for photovoltaic installations alongside rail road tracks and motorways. The length of rail road tracks and motorways has been derived from [Eurostat 2015] except the length of rail road tracks in Austria, Denmark, and Netherlands which has been derived from [Lexas 2015].

According to [IWES PV 2012] 110 m at both sides alongside rail road tracks and motorways are theoretical available for photovoltaic installations. Thereof 20% is technical useable and it has been assumed that 33% of this 20% are occupied with photovoltaic panels.

Table 7 shows the technical potential for electricity from photovoltaic power plants on green and brown fields.

Table 7: Technical potential for electricity from photovoltaic power plants alongside rail road tracks and motorways

State	Railway	Motorway	PV panel area	PV potential	
	(km)	(km)	(km²)	min (TWh/yr)	max (TWh/yr)
Austria	6,399	1,719	27	4	6
Belgium	6,436	1,763	10	1	2
Bulgaria	5,658	541	28	4	7
Croatia	4,090	1,295	12	2	3
Cyprus	0	257	0	0	0
Czech Republic	15,636	751	51	6	9
Denmark	2,667	1,128	7	1	1
Estonia	2,146	140	4	0	1
Finland	8,523	810	116	12	18
France	51,217	11,465	1,391	203	309
Germany	41,328	12,917	1,458*	196	299
Greece	3,062		16	3	4
Hungary	13,378	1,515.1	56	8	11
Ireland	2,421	897	9	1	2
Italy	24,277	6,726	371	58	89
Latvia	2,161		6	1	1
Lithuania	2,184	309	7	1	1
Luxemburg	275	152	0	0	0
Malta	0		0	0	0
Netherlands	2,896	2,631	8	1	1
Poland	36,939	1,482	476	64	98
Portugal	2,541	2,988	21	4	6
Romania	20,284	644	202	34	52
Slovakia	3,631	419.2	8	1	2
Slovenia	2,178	770	2	0	1
Spain	19,285	14,701	690	124	189
Sweden	15,601	1,891	292	33	50
UK	31,324	3,685.7	344	39	59
Total EU 28	326,538	71,597	5,611	799	1,219

* includes 670 km² of PV panel area on impervious surfaces area [IWES PV 2012]

Following this, the technical PV potential in the EU is some 1,472 to 2,245 TWh$_e$ per year.

By 2014 cumulative solar PV installations reached some 88.6 GW in Europe generating about 90 TWh of electricity per year. The vast potential of PV has thus still to be lifted.

Solarthermal power (SOT)

[Klaiß et al. 1992] and [Trieb et al. 2005] assessed the technical potential for solarthermal (SOT) power generation in the Mediterranean's and the Middle East. The calculations are still quite robust as there have been no fundamental changes in SOT technical performance figures since then. According to above-captioned studies, the technical potential for SOT power is between 1,404 and 2,239 TWh_e per year.

SOT requires high shares of direct solar irradiation. SOT potentials can thus also be lifted with photovoltaic technology. However, SOT technology is not suited to tap PV potentials.

Hydro power

River

Assumptions for the overall technical potential for inland hydro power vary to a great extend between the different potential studies analysed. The resulting technical potentials are notably dependent from the future development of the regulatory framework. In EU Member States that already have significant hydro power installations, such as Switzerland or Norway, new hydro power plants typically fail to receive the required public acceptance for ecological and social reasons. The technical potential for renewable electricity from hydro power in EU-28 is assumed 576 to 631 TWh_e per year.

With some 380 TWh_e, inland hydro power plants provided by far the largest share (45.5%) of electricity from all renewable electricity sources in the EU-28 in 2013 [Eurostat 2015].

Ocean

Besides established river (runoff) hydro power generation, there are notable development and demonstration efforts for tidal and wave energy in France and the United Kingdom [Eurostat 2015]. To date, ocean energy supplies some 0.05% of the total electricity generated from renewable energy sources in the EU-28 in 2013. According to [Salter 2000], the technical electricity generation potential from wave energy in Europe is 600 TWh per year. According to [IWES 2012], the potential of ocean energy of selected European countries is 900 TWh per year. A bandwidth of 600 to 900 TWh_e/a is thus assumed as technical potential from tidal and wave energy in the EU.

Geothermal power

According to [Kaltschmitt et al. 1/1997], [TAB 2003], [Stefansson 2005], and [MNH 2005], the technical potential for geothermal power (without 'fracking') is between 44 to 83 TWh_e per year in the EU-28.

The capacity of the 51 geothermal power plants in operation is about 0.95 GW_e. Sweden, Germany and Italy are the countries with highest installed capacity of geothermal energy in the EU-28. Geothermal energy provided about 0.2% of the total EU final electricity demand in 2012 [JRC 2015].

Results

The technical production potential from renewable electricity sources in Europe is depicted in Figure 6 (by energy source) and Figure 7 (by member state).

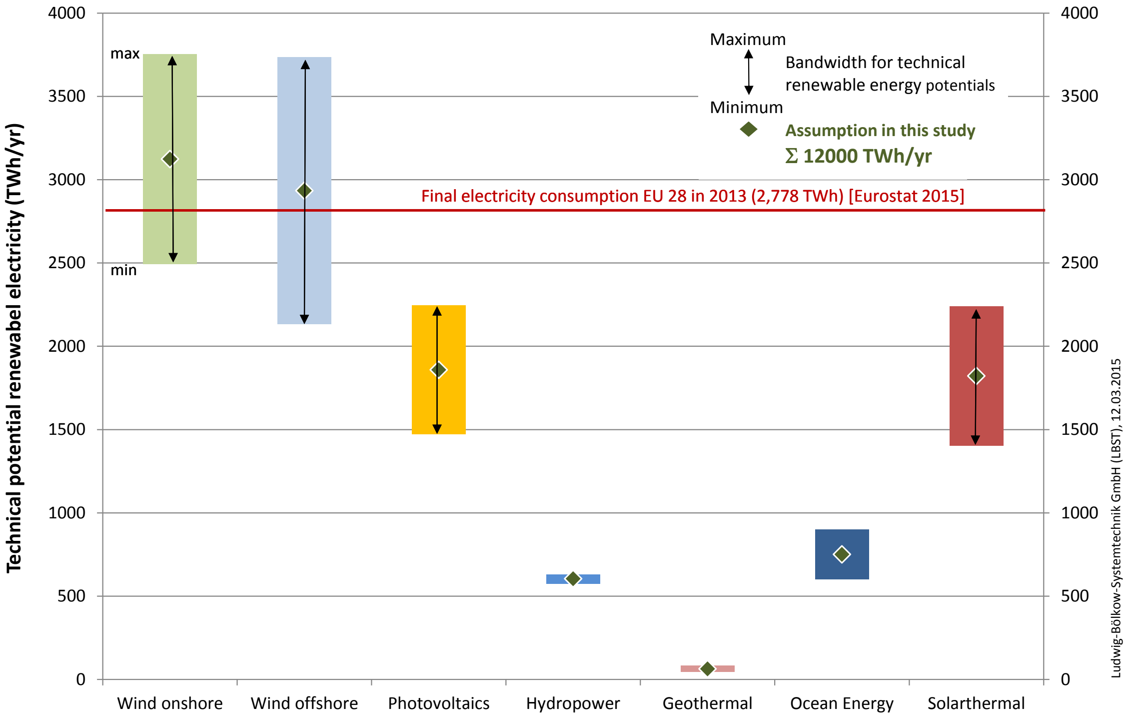


Figure 6: Renewable electricity potentials in EU-28, depicted by source

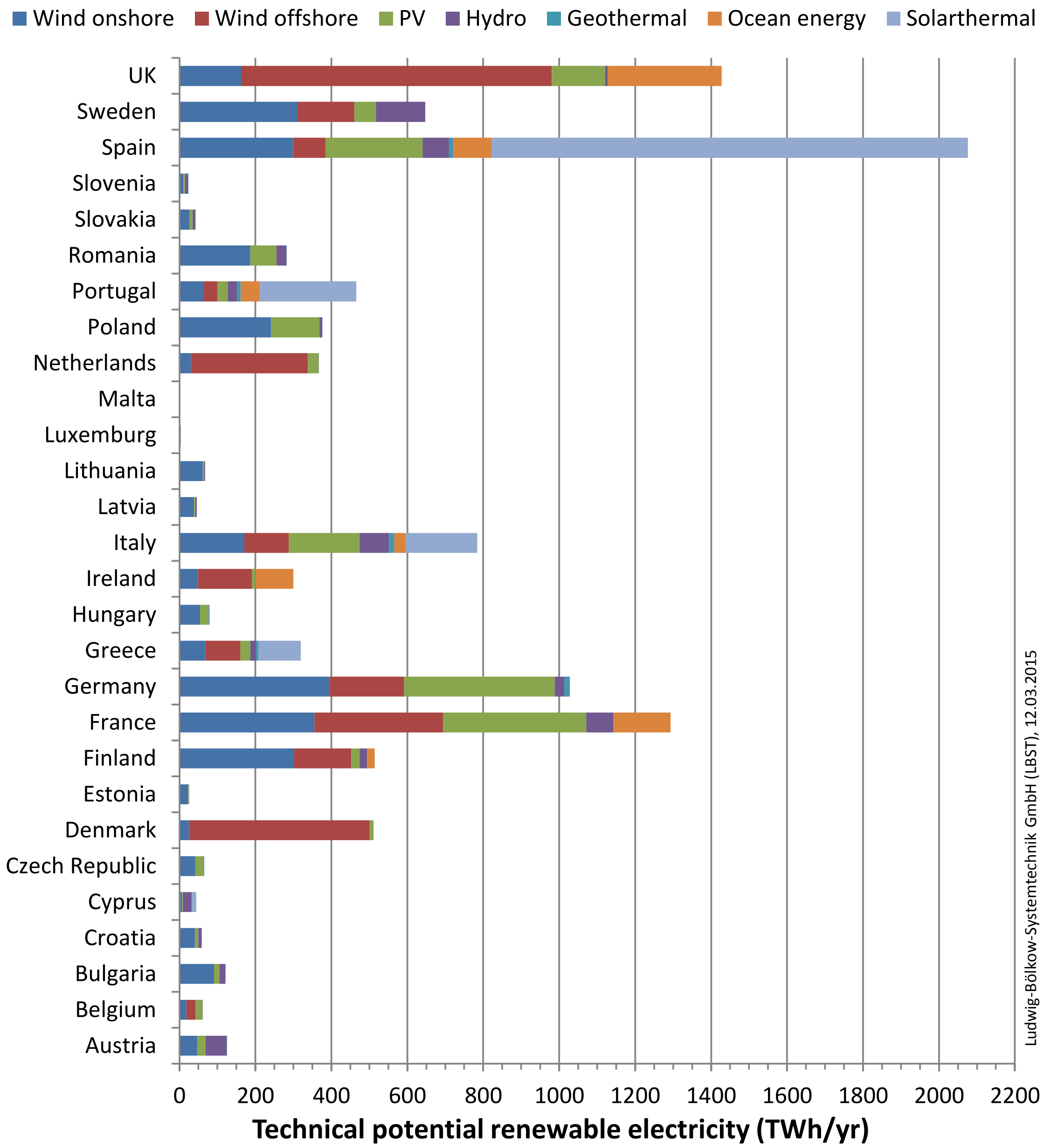
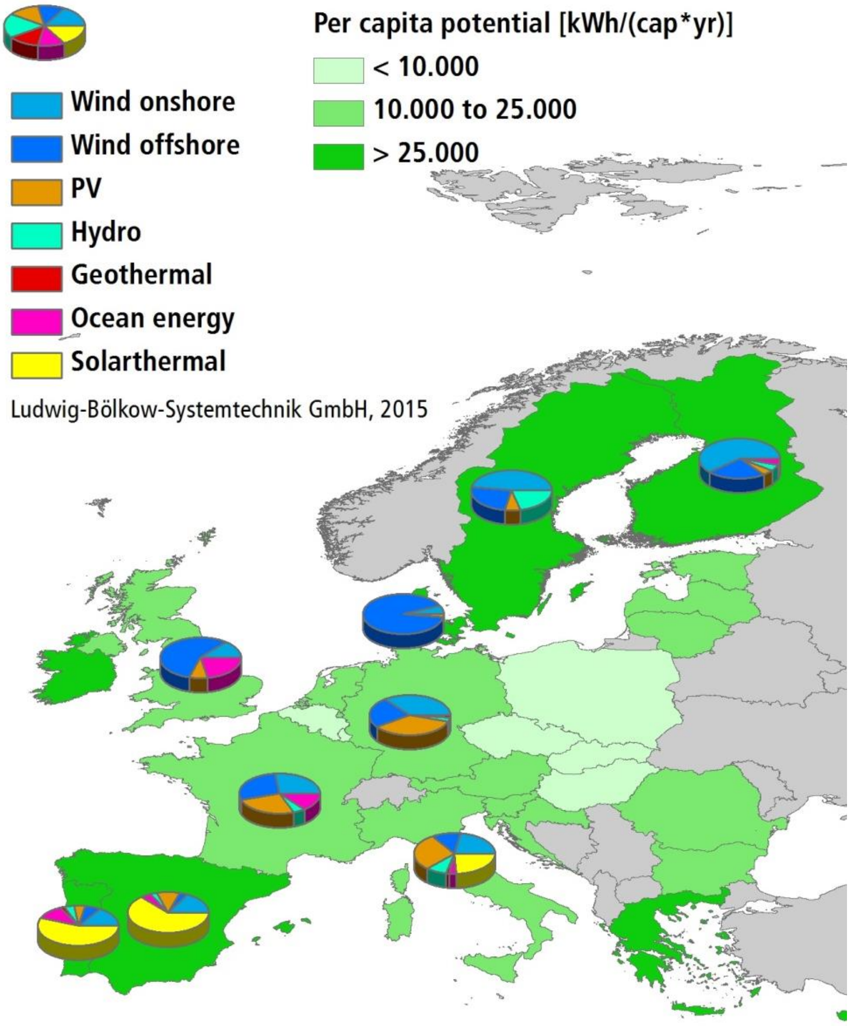


Figure 7: **EU renewable electricity potentials, depicted by Member State**

The EU has significant technical renewable electricity supply potentials, mainly from wind onshore, wind offshore and photovoltaics. Conservative assumptions result in an overall renewable electricity potential of 9,000 TWh_e per year. Assuming more progressive installation density and yield parameters result in renewable electricity supply potentials of 14,000 TWh_e per year. For comparison, in 2013 the net electricity consumption in EU-28 was 2,778 TWh [Eurostat 2015], thus the renewable electricity potentials exceed current electricity consumptions by a factor of 3 to 5.

For this study, a conservative technical renewable electricity potential of 9,000-12,000 TWh/a is assumed for the EU-28. As per today, only some 6% of this renewable electricity potential has already been exploited in the EU-28. Figure 8 depicts EU Member States by their technical renewable electricity potential per capita.



Ludwig-Bölkow-Systemtechnik GmbH, 2015

Figure 8: **Per capita renewable electricity potentials in EU-28**

From Figure 8 it can be seen that Denmark, Finland, Greece, Ireland, Portugal, Spain and Sweden are EU Member States with high per capita renewable electricity production potentials.

3.1.3 Comparison of renewable electricity with bioenergy

As depicted in the first FVV Future Fuels study [FVV 2013] and other LBST analyses, e.g. in the context of the mobility and fuel strategy of the German Government [MKS 2015], there are fundamental differences in the specific energy yields per area between agro bioenergy and wind/solar power. This is due to the fact that the efficiency of the photosynthesis process is typically below 1% solar-to-biomass. Some algae achieve solar-to-algae biomass efficiencies of 1.1 to 3.2% [Steiner 2010] under optimal conditions. Compared to this, conversion efficiencies of photovoltaic systems are typically greater than 15% solar-to-electricity.

3.1.4 Spotlight on material resources

In the course of the discussions on renewable electricity supply potentials, FVV working group members raised the question regarding potential material resource demands from an energy transition ('Energiewende') in the transportation sector. Although outside of the scope of this study, in the following the two examples steel production and copper demands are briefly discussed.

With a view to world **steel** production, Figure 9 depicts the historic development of crude steel production by major countries worldwide. This gives an imagination, how severe the consumption growth in China, which is reflected by its production, influences the demand for material resources. Almost all additional steel production since 2000 can be attributed to China. The economic crisis in 2008 had a strong impact on steel production / consumption in OECD-countries but almost no influence on Chinese growth rates. This was different to the present shrinking of steel production which predominantly is due to China.

The light green area in the Figure 9, which ends in 1991, shows the production volume in the former Soviet Union. Its succeeding countries are explicitly referenced beyond 1991 (purple and green areas). Data for 2015 are extrapolated from the first three quarters to the full year.

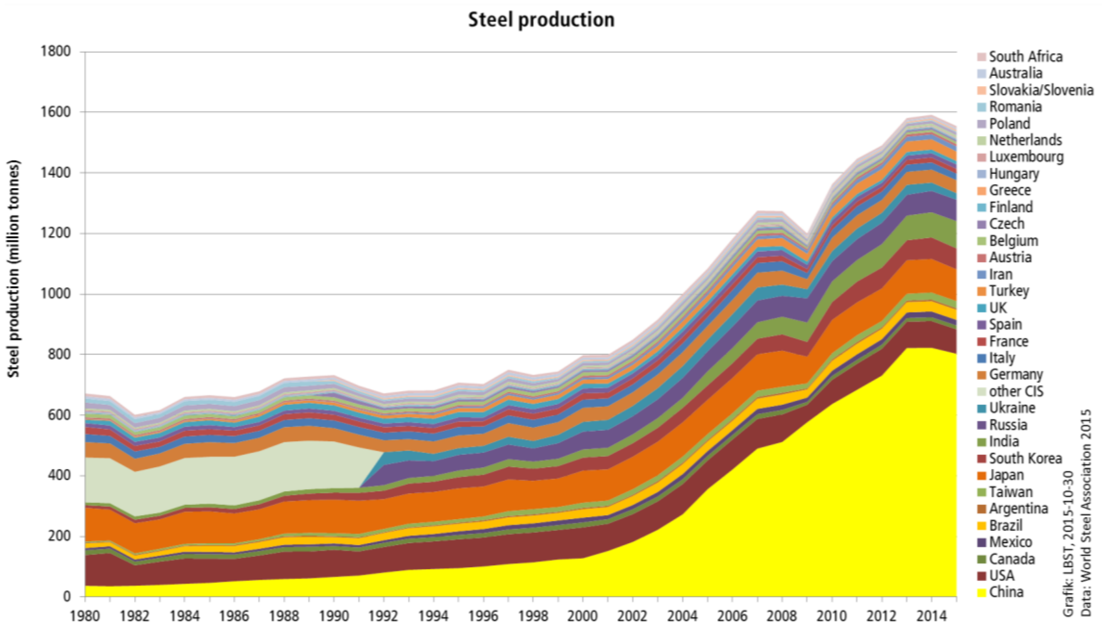


Figure 9: **Historical development of crude steel production worldwide (Image: LBST, Data: [WSA 2015])**

To give an example on rising material demand of new technologies and its relation to other uses, LBST has modelled EU **copper** demands from 1,300 MW installed wind power plants and sensitivities for 'ICE passenger cars only' (see Figure 10) as well as 'BEV/REEV passenger cars only' (see Figure 11). For the purpose of this sensitivity analysis, all other copper material uses in Europe are kept constant.

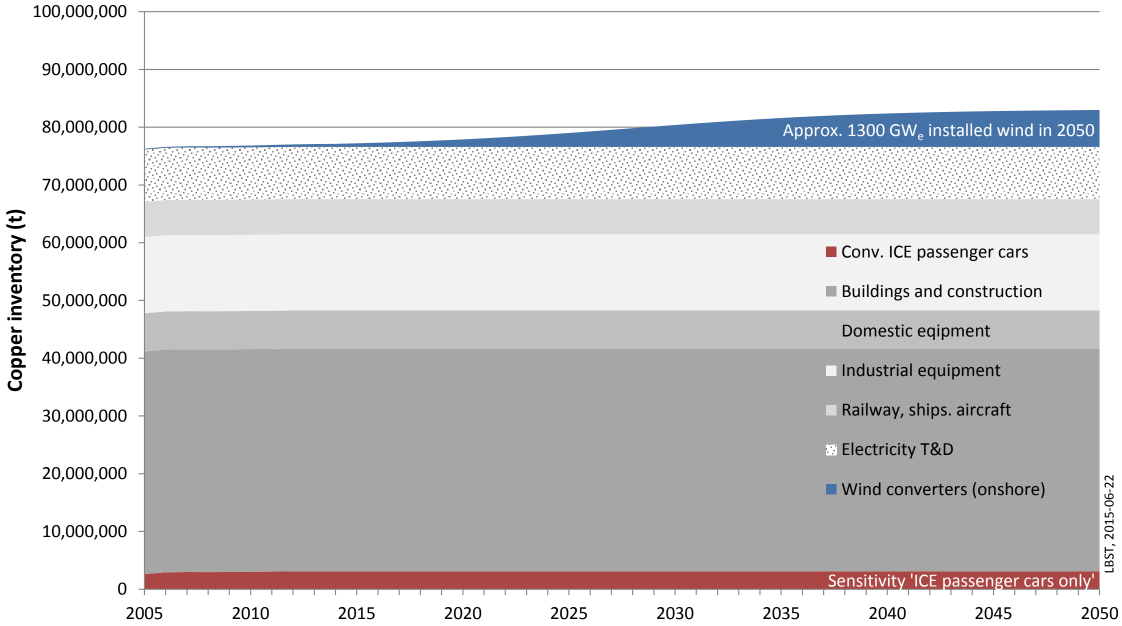


Figure 10: Copper material use for onshore wind power and ICE passenger cars only in the EU (Image: LBST)

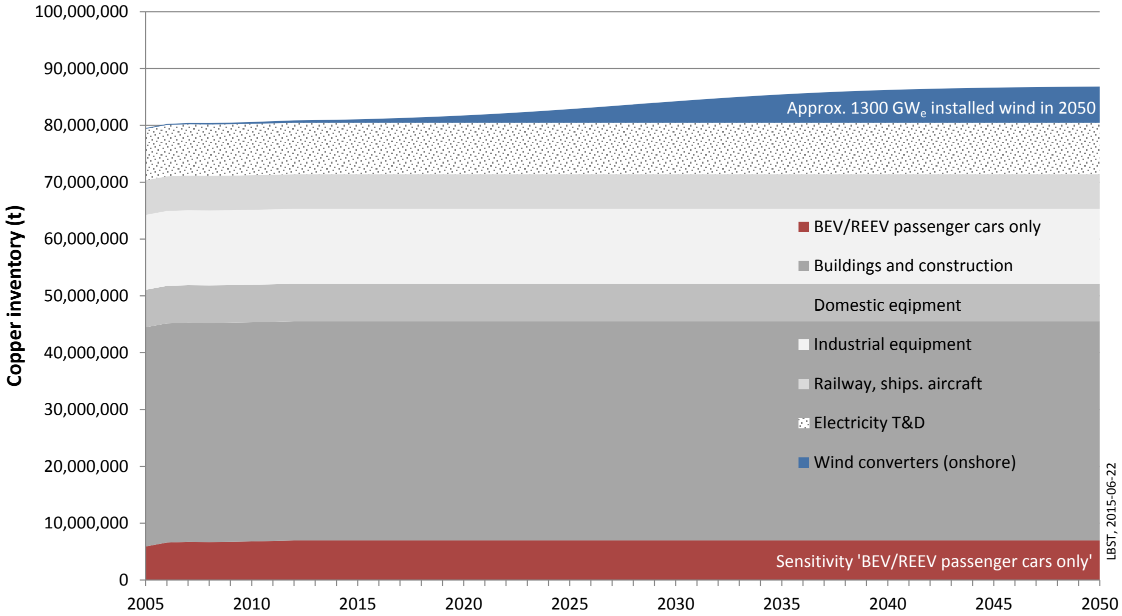


Figure 11: Copper material use for onshore wind power and BEV/REEV passenger cars in the EU (Image: LBST)

As can be seen from Figure 10 and Figure 11 for Europe,

- copper use for onshore wind is below the use of copper in electricity transport and distribution infrastructure; and
- copper use in passenger cars almost doubles in the 'BEV/REEV only' case.

Of course the imbedded copper in buildings, infrastructure usually has a long product life time, before it might be available for recycling. It is estimated that about 60-70% of the world-wide cumulative copper production volume is still in use.

3.1.5 Conclusions from renewable electricity potentials

The following conclusions can be drawn from the assessment of technical renewable electricity potentials in Germany and Europe:

- The technical potentials for the production of renewable electricity are significant, notable when compared with bioenergy sources.
- In the light of further cost reductions in renewable power generation from wind and solar, the realistic level of exploitation of these potentials is rather limited by the public acceptance than costs.
- Electricity potentials estimated for solar-thermal power plants (SOT) could also be exploited with PV technology. Power generation costs from SOT will remain higher than PV power generation costs. SOT is attractive because heat storage integration increases the annual equivalent full load hours compared to PV and wind power.

3.2 Renewable electricity scenario

3.2.1 Approach and methodolgy

A host of (renewable) long-term energy supply scenarios have been developed in recent years, especially for **Germany**, e.g.

- Energiesystem Deutschland [ISE 2013], i.A. BMWi
- THG-neutraler Verkehr 2050 [Öko-Institut 2013], i.A. UBA
- Renewbility II [Öko-Institut et al. 2013], i.A. UBA
- eMobil [Hacker et al. 2014]
- Verbändekonzept [WWF et al. 2014]
- Treibhausgasneutraler Verkehr 2050 [INFRAS et al. 2015], i.A. UBA

but also for **Europe**, e.g.

- Energy [r]evolution (Greenpeace 2012)
- TYNDP Scenario Development (ENTSO-E 2015)

The future worlds described by these scenarios vary significantly with regard to the underlying assumptions. From a practical perspective, there are different scopes (sectors included, …), technical options and technology specific costs taken into account. Transportation has entered the 'Energiewende' scenarios in all its aspects in the last few years only. A comprehensive appraisal regarding the role of renewable power for fuels – like this study aims to – has only begun in Germany. Discussions in EU Member States and at the European level are in its infancy. Thus, these energy scenarios underestimate the need for the deployment of renewable power plants that serve additional power demands for electricity-based fuels. Additional power demands can be in the order of today's electricity demands, subject to the transportation demands, powertrain options, and renewable fuels assumed for the future [MKS 2015].

For this reasons, renewable energy scenarios from established studies cannot be taken 'as is'. A synthetic scenario for the roll-out of renewable power plants has thus been chosen for the purpose of this study. For this, the following S-curve formula is used:

$$f(t) = G \cdot \frac{1}{1 + e^{-k \cdot G \cdot t}\left(\frac{G}{f(0)} - 1\right)}$$

Above S-curve formula is then fitted to match each renewable power sources' historic roll-out with its technical availability potentials in 2050. This procedure is applied to Germany and major EU Member States and results in the renewable power mix for Germany and

EU 28 respectively. The specific electricity costs are then calculated based on the renewable power mixes.

3.2.2 German renewable electricity mix and costs

Figure 12 shows a possible development of electricity generation from wind power (onshore and offshore), photovoltaic (PV), hydro power, and geothermal power stations in Germany.

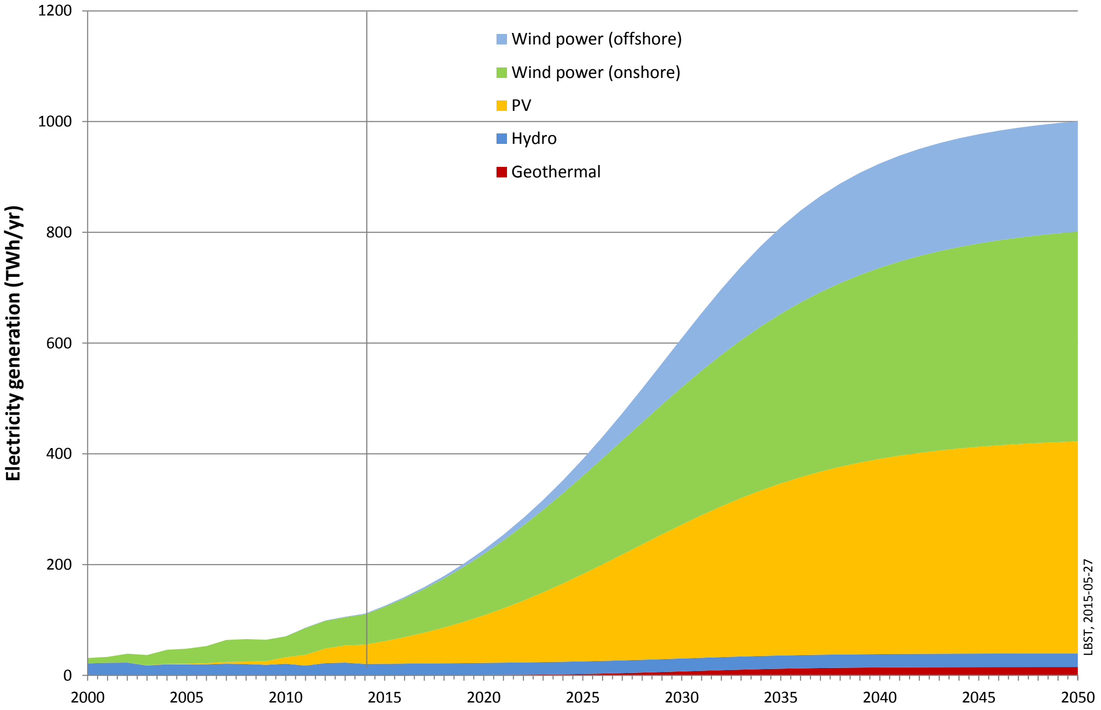


Figure 12: **Renewable electricity supply scenario for Germany wherein historic developments are extrapolated to exploit technical supply potentials by 2050**

Based on data from [IWES 2013] and [Fichtner & Prognos 2013] (for wind power) and [ISE 2015] (for solar power) and the composition of the additions of wind and photovoltaic power stations shown in Figure 12 the cost of electricity from an electricity generation mix of wind and photovoltaic power plants has been calculated.

Table 8 shows the cost of electricity from new wind and photovoltaic power plants in Germany.

Table 8: **Cost of electricity from new wind and photovoltaic power plants in Germany (cent/kWh)**

	2015	2020	2030	2040	2050
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	10.1	8.6	7.2	6.2	5.4
Weighted mix	9.2	8.1	7.3	6.6	6.0

Table 9 and Figure 13 show the electricity cost of the total plant inventory (including existing plants) by technology and the resulting mix. A lifetime of 20 years has been assumed both for wind and photovoltaic power plants to calculate the annual increment of new plants.

Table 9: **Electricity cost of total plant inventory (by technology, mix) in Germany (cent/kWh)**

	2015	2020	2030	2040	2050
Wind onshore	8.5	8.1	7.5	6.8	6.4
Wind offshore	13.9	11.5	9.0	8.2	7.4
Photovoltaic	10.1	9.3	8.1	6.9	6.0
Weighted mix	**9.2**	**8.7**	**8.0**	**7.2**	**6.5**

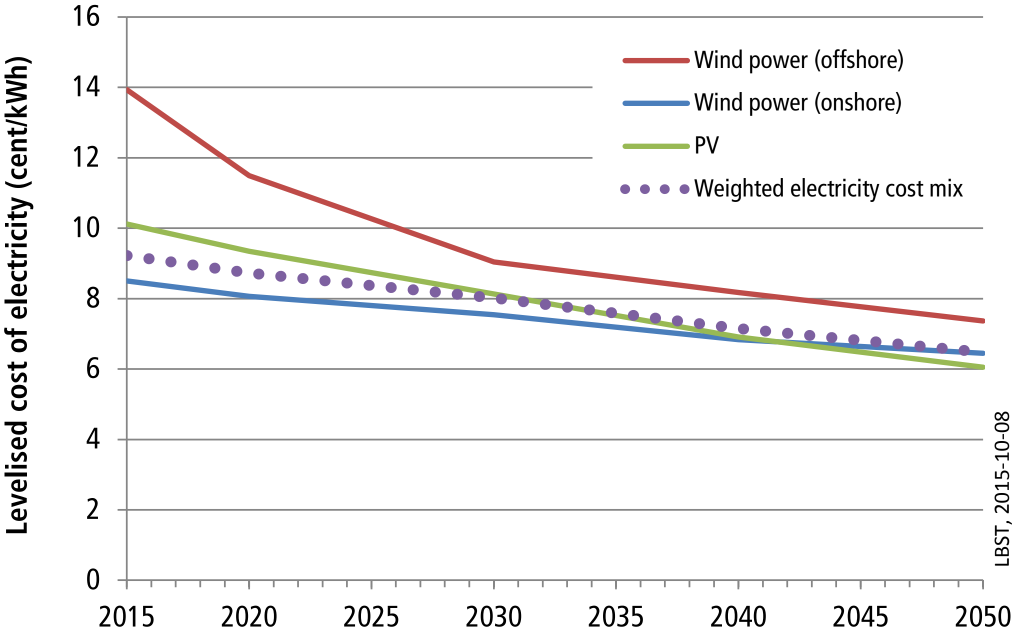


Figure 13: **Electricity cost of total plant inventory (by technology and mix) in Germany**

The costs for electricity transport and distribution has been added to calculate the electricity cost at the power-to-gas (PTG) and power-to-liquid (PTL) plant. The costs for electricity transport and distribution have been derived from typical today's fees for grid usage published by a grid operator. Table 10 shows the fees for consumers connected with the ultra-high voltage (UHV), high voltage (HV), medium voltage (MV), and low voltage (LV) grid.

Table 10: Costs for electricity transport and distribution

	Einheit	<2500 h	>2500 h	Reference
Energy rate (cumulative)				
UHV (220 kV, 380 kV)	€/kWh	0.0199	0.0026	50hertz 2013
UHV, HV (110 kV)	€/kWh	0.03	0.0066	WEMAG 2013
UHV, HV, MV (10-20 kV)	€/kWh	0.0442	0.0176	WEMAG 2013
UHV, HV, MV, LV (0.4 kV)	€/kWh	0.0503	0.0161	WEMAG 2013
Demand rate (cumulative)				
UHV (220 kV, 380 kV)	€/(kW*a)	7.32	50.69	50hertz 2013
UHV, HV (110 kV)	€/(kW*a)	12.95	71.52	WEMAG 2013
UHV, HV, MV (10-20 kV)	€/(kW*a)	24.53	90.85	WEMAG 2013
UHV, HV, MV, LV (0.4 kV)	€/(kW*a)	25.14	110.66	WEMAG 2013

Additionally a concession levy of 0.0011 €/kWh for industrial consumers and 0.0199 €/kWh for households (charging BEV) have been added.

The equivalent full load period of the PtX plant has been assumed to be 4000 hours per year leading to about 4.1 cent per kWh of electricity for a PtX plant connected with the medium voltage grid and about 1.6 cent per kWh of electricity for a PtX plant connected with the ultra-high voltage grid.

The costs of electricity transport and distribution are different in the different regions, and even within the EU Member States. However, a detailed analysis for all European countries cannot be carried out in this study. Therefore, the same costs for electricity transport and distribution have been assumed both for Germany and for the EU.

3.2.3 EU renewable electricity mix and costs

Figure 14 shows a possible development of electricity generation from wind power (onshore and offshore), photovoltaic (PV), hydro power, and geothermal power stations in the EU.

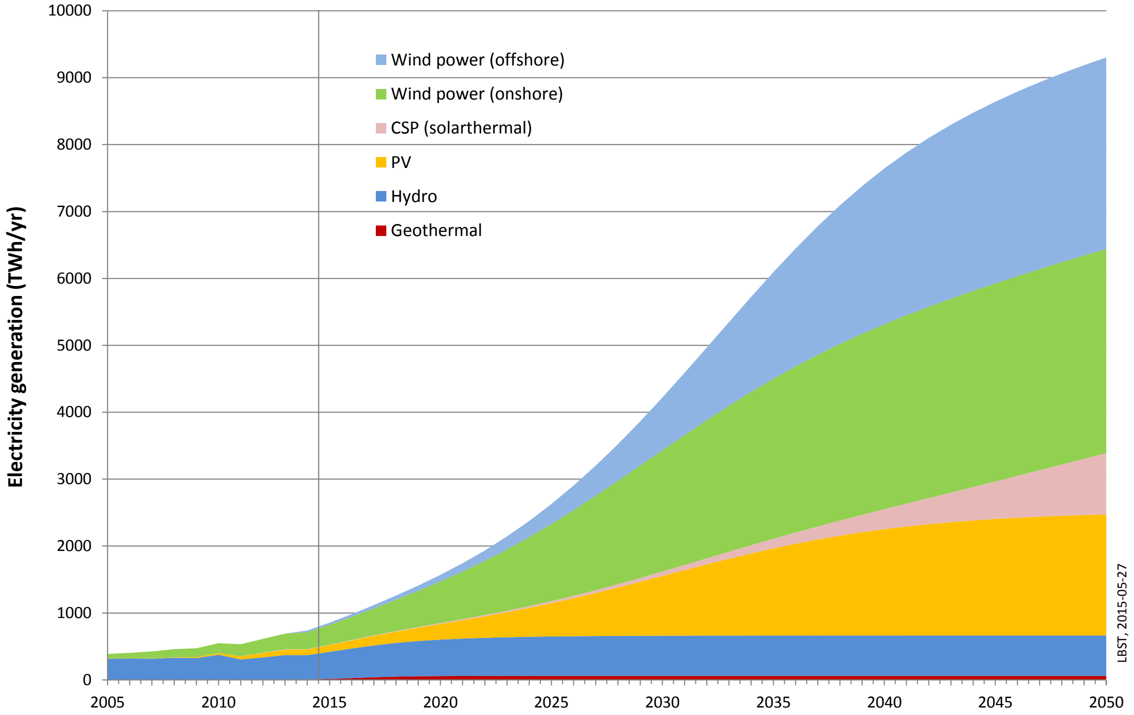


Figure 14: **Renewable electricity supply scenario for EU-28 wherein historic developments are extrapolated to exploit technical supply potentials by 2050**

Based on data from [IWES 2013] and [Fichtner & Prognos 2013] (for wind power) and [ISE 2015] (for solar power) and the composition of the additions of wind and photovoltaic power stations shown in Figure 14 the cost of electricity from an electricity generation mix of wind and photovoltaic power plants has been calculated.

The calculation of the specific electricity cost of total plant inventory (consisting of onshore wind, offshore wind, and PV) in the EU is based on a weighted mix of the electricity generation costs of Austria, France, Germany, Greece, Italy, Romania, Spain, and UK which represent an adequate mix of the different locations. For offshore wind farms in United Kingdome the variant with lower water depth described in [Fichtner & Prognos 2013] has been selected.

Table 11 shows the cost of electricity from new wind and photovoltaic power plants in selected EU countries.

Table 11: **Cost of electricity from new wind and photovoltaic power plants in selected EU states**

	2015 (cent/kWh)	2020 (cent/kWh)	2030 (cent/kWh)	2040 (cent/kWh)	2050 (cent/kWh)
Austria					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	8.5	7.3	6.0	5.2	4.5
Weighted mix	8.5	7.5	6.7	6.1	5.6
France					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	7.9	6.8	5.6	4.9	4.2
Weighted mix	8.4	7.3	6.3	6.0	5.7
Germany					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	10.1	8.6	7.2	6.2	5.4
Weighted mix	9.2	8.1	7.3	6.6	6.0
Greece					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	6.7	5.8	4.8	4.2	3.6
Weighted mix	7.7	6.8	6.2	6.1	6.2
Italy					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	7.2	6.2	5.1	4.5	3.8
Weighted mix	7.8	6.8	6.2	5.7	5.5
Poland					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	10.1	8.6	7.2	6.2	5.4
Weighted mix	8.5	7.5	7.0	6.4	5.9
Romania					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	9.2	7.9	6.5	5.7	4.9
Weighted mix	8.6	7.6	6.9	6.3	5.8
Spain					
Wind onshore	8.5	7.5	7.0	6.5	6.1
Wind offshore	13.9	10.8	8.5	7.5	6.9
Photovoltaic	6.2	5.3	4.4	3.8	3.3
Weighted mix	8.2	7.1	6.0	5.4	5.1

	2015 (cent/kWh)	2020 (cent/kWh)	2030 (cent/kWh)	2040 (cent/kWh)	2050 (cent/kWh)
UK					
Wind onshore	7.8	6.9	6.4	6.0	5.6
Wind offshore	12.8	10.2	8.5	7.5	6.9
Photovoltaic	10.4	8.9	7.4	6.4	5.5
Weighted mix	10.1	9.1	8.2	7.2	6.5

Table 12 show the electricity cost of the total plant inventory (including existing plants) by technology and the resulting mix in selected EU states.

Table 12: Electricity cost of total plant inventory (by technology, mix) in selected EU states

	2015 (cent/kWh)	2020 (cent/kWh)	2030 (cent/kWh)	2040 (cent/kWh)	2050 (cent/kWh)
Austria					
Wind onshore	8.5	8.1	7.5	6.8	6.4
Wind offshore	13.9	13.9	13.9	7.8	7.8
Photovoltaic	8.5	7.8	6.6	5.7	5.1
Weighted mix	8.5	8.0	7.3	6.4	6.0
France					
Wind onshore	8.5	7.9	7.3	6.9	6.4
Wind offshore	13.9	10.9	8.5	7.5	7.4
Photovoltaic	7.9	7.0	6.0	5.5	4.7
Weighted mix	8.4	7.6	6.6	6.4	6.1
Germany					
Wind onshore	8.5	8.1	7.5	6.8	6.4
Wind offshore	13.9	11.5	9.0	8.2	7.4
Photovoltaic	10.1	9.3	8.1	6.9	6.0
Weighted mix	9.2	8.7	8.0	7.2	6.5
Greece					
Wind onshore	8.5	8.0	7.4	6.8	6.4
Wind offshore	13.9	11.0	8.6	7.5	7.1
Photovoltaic	6.7	6.3	5.6	4.6	4.1
Weighted mix	7.7	7.3	6.8	6.4	6.5
Italy					
Wind onshore	8.5	8.0	7.5	6.9	6.4
Wind offshore	13.9	10.9	8.6	7.5	7.2
Photovoltaic	7.2	6.8	6.0	4.9	4.3
Weighted mix	7.8	7.4	6.8	6.1	5.8
Poland					
Wind onshore	8.5	7.9	7.3	6.8	6.4

	2015 (cent/kWh)	2020 (cent/kWh)	2030 (cent/kWh)	2040 (cent/kWh)	2050 (cent/kWh)
Wind offshore	13.9	13.9	13.9	7.8	7.8
Photovoltaic	10.1	8.9	7.3	6.3	5.9
Weighted mix	8.5	7.9	7.3	6.7	6.3
Romania					
Wind onshore	8.5	8.0	7.4	6.8	6.4
Wind offshore	13.9	13.9	13.9	7.8	7.8
Photovoltaic	9.2	8.4	7.0	6.2	5.5
Weighted mix	8.6	8.1	7.3	6.6	6.2
Spain					
Wind onshore	8.5	8.0	7.6	6.8	6.5
Wind offshore	13.9	11.3	8.8	7.7	7.3
Photovoltaic	6.2	5.6	4.7	4.3	3.7
Weighted mix	8.2	7.6	6.5	5.8	5.5
UK					
Wind onshore	7.8	7.4	6.9	6.3	5.9
Wind offshore	12.8	10.8	9.0	8.4	7.2
Photovoltaic	10.4	8.9	7.4	6.8	6.0
Weighted mix	10.1	9.6	8.6	7.9	6.9

Table 13 and Figure 15 show the electricity cost of the total plant inventory (including existing plants) by technology and the resulting mix in the EU.

Table 13: Electricity cost of total plant inventory (by technology, mix) in the EU (cent/kWh)

	2015	2020	2030	2040	2050
Wind onshore	8.5	8.1	7.5	6.8	6.4
Wind offshore	12.9	10.8	9.0	8.2	7.3
Photovoltaic	8.6	7.9	6.5	5.8	5.1
Weighted mix	**8.8**	**8.3**	**7.6**	**6.9**	**6.3**

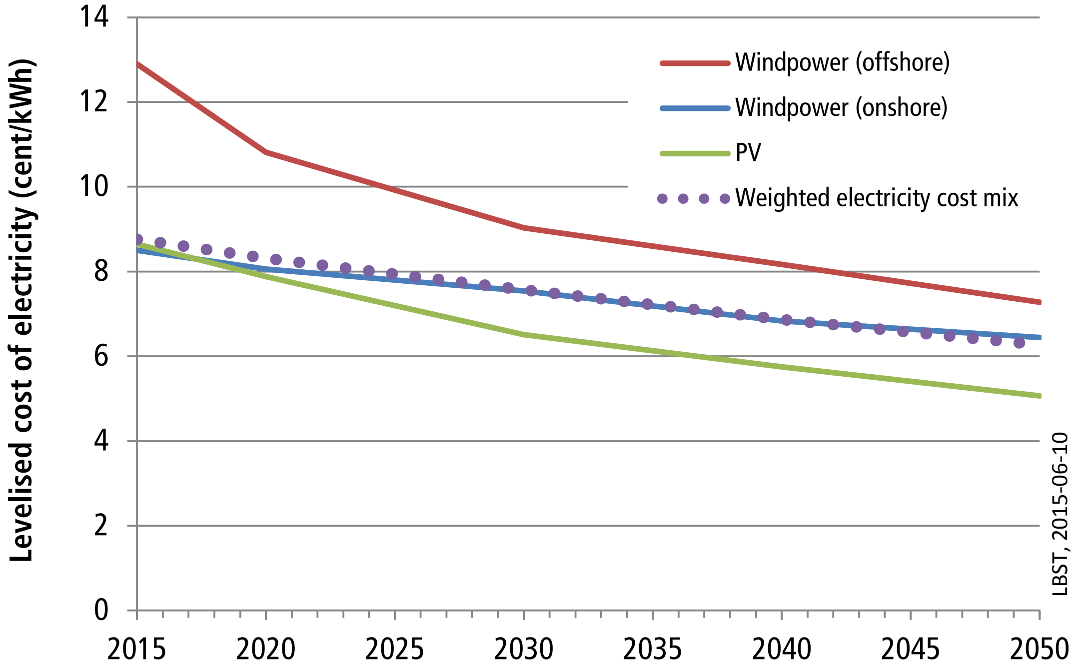


Figure 15: Electricity cost of total plant inventory (by technology and mix) in the EU

3.2.4 Import full cost renewable electricity generation («best-case»)

For a best case scenario it has been assumed that the PtL plant is located onsite a large concentrating solar power (CSP) station with thermal storage. As a result the equivalent full load period increases from 4,000 hours per year to **6,500 hours per year** and no electricity transport and distribution is required.

Table 14: Concentrating solar power station [DLR et al 2012]

Parameter	Unit	2020	2030	2050
Capacity	MW_e	200	200	200
Equivalent full load period	h/yr	5,500	6,000	6,500
Investment	million €	1,040	880	760
	€/kW_e	5,200	4,400	3,800
Operating and maintenance	million €/yr	31.2	26.4	22.8
	€/(kW_e*yr)	156	132	114

For an interest rate of 4% and a depreciable life of 25 years the electricity generation costs amount to about **5.5 cent per kWh** of electricity in 2050. The PtL plant is described in chapter 5.1.6.

4 DEFINITION AND MODELLING OF TWO TRANSPORTATION DEMAND SCENARIOS

The demand for fuel and corresponding emissions are directly linked with the development of the transportation sector. Mobility behaviour will be characterised by developments that cannot be clearly projected today for the 35 years to come until 2050. Therefore a differentiation of the scenarios in form of development borders is targeted.

In consultation with the FVV working group on »Future Fuels«, two scenarios for the passenger (pkm) and the freight transport demand (tkm) were defined. On the one hand they maintain conservative behaviour, on the other hand they take indicators for change of tendency into consideration as well, as they are for example represented by the reduction of the still dominant motorised private transport or the increased share of rail-bound heavy-duty traffic. As far as possible, these scenarios were based on already existing studies and assessments.

Published transportation demand scenarios until 2050 have been evaluated (chapter 4.1). Together with the FVV working group, two distinct scenarios with upper (HIGH) and lower (LOW) demand projections were selected for Germany and the EU respectively. Based on these transport demand projections various supply scenarios were derived and evaluated (chapter 4.2). Gaps in the assumptions were filled by own assessments and calculations.

4.1 Passenger and freight transportation demand and scenario selection

4.1.1 Germany

The list of scenario projections from a literature review covers:

- eMobil 2050 (Öko-Institut, 2014) [Hacker et al. 2014]
- Klimafreundlicher Verkehr Deutschland 2050, (Verbändekonzept (WWF, BUND, Germanwatch, Nabu VCD, 2014) [WWF et al. 2014]
- BMUB Aktionsprogramm Klimaschutz 2050 (2014) [Repenning et al. 2014]
- UBA THG-neutraler Verkehr 2050 [Öko-Institut 2013]
- Energiekonzept Bundesregierung (2010) [ewi et al. 2010]
- BMU Leitstudie [DLR et al. 2012]
- BMVI Verkehrsprognose 2030 [BVU et al. 2014]
- Shell Pkw-Szenarien bis 2040 (2015) [Shell 2015]
- Renewbility II – Scenario für einen anspruchsvollen Klimaschutzbeitrag des Verkehrs (UBA 2013) [Öko-Institut et al. 2013]
- EWI/GWS/Prognos 2014 [BMWI 2014]
- Verkehrsprognose 2030 [BVU et al. 2014] / MKS 2050 [MKS 2015]

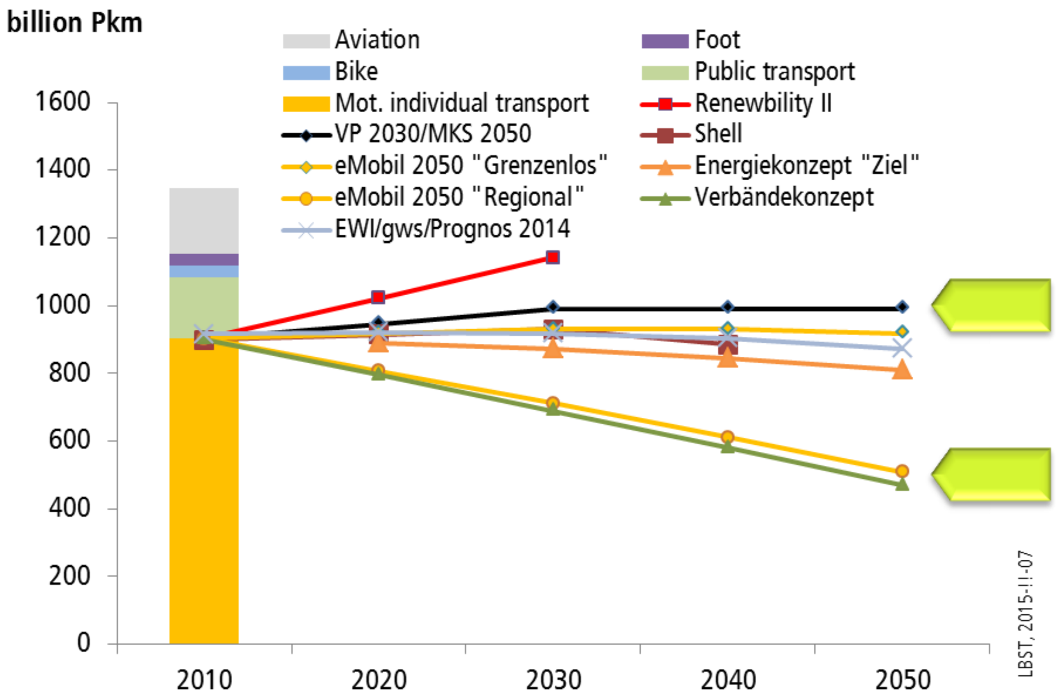


Figure 16: **Exemplary overview over motorised individual passenger transport scenarios for Germany (arrows = boundary scenarios selected for this study)**

Figure 16 shows the split of the passenger transport demand in 2010 and the development of motorized individual passenger transport demand until 2050 as an example. The different bars for 2010 represent the individual contributions of different transport modes in 2010. However, scenarios for the development of passenger transport demand for all transport modes have been modelled.

The **orange bar** represents the motorized individual transport (MIV – motorisierter Individualverkehr / motorised individual transport). As most of the studies focus on individual road transport, its development until 2050 is further described:

- By far the lowest transportation demand in 2050 is expected in the Verbändekonzept (Klimafreundlicher Verkehr 2050) and eMobil 2050 'Regional'. These two studies are very close to each other and match the expectation of an aggressive transport policy towards climate neutral transport, including modal shift and sufficiency.
- By far the highest demand is expected in the Study 'Renewbility II' from 2013. The projection horizon ends in 2030. Empirical data since 2009 exhibit that the recent development does not match with these expectations. All later studies expect a reduced demand against 'Renewability II'.

- The ‘Verkehrsprognose 2030’ and its extrapolation to 2050 by the MKS study group (VP2030/MKS2050) represent an upper expectation on future demand. MKS expects that the individual road transport grows until 2030 as projected in ‘Verkehrsprognose 2025’ and beyond stays flat until 2050. Due to the reduced growth expectation in the recently published VP 2030 the present data are adapted correspondingly. This reduces the motorized individual transport from 1019 billion Pkm (+ 13%; VP 2025) to 992 billion Pkm (+10%) for the period 2030 to 2050.
- Though close to ‘VP2030/MKS2050’, but with a slightly reduced demand expectation is the upper scenario of eMobil 2050 ‘Grenzenlos’ (without limits).
- Until 2030 this scenario almost coincides with the ‘Shell’-scenario 2040.
- Somewhere in between is the projection of the ‘Ziel’-scenario of the Energy concept of the German Government from 2010.

The **green bar** represents the demand for public transport. This includes road transport (buses) as well as inner city tramways and short and long distance transport with railways. Figure 16, beyond motorized individual transport, shows the development of different projections until 2050 for the other modes. It becomes obvious that the public transport sector remains small in almost all projections. Only in the scenario eMobil 2050 public transport more than doubles as a consequence that individual transport demand is reduced by various incentives.

Light and dark blue bars in Figure 16 show the contribution from non-motorized mobility walking and biking. Though an important contribution by the number to trips per day its influence on the energy demand from motorized transport is marginal. Therefore, in the context of the present study these two modes are not evaluated.

The final **grey bar** shows the contribution from air transport. As eMobil 2050 concentrates its analysis on surface transport, air transport was not considered there.

The large **green arrows** in Figure 16 mark the two scenario projections which are selected as upper and lower bound scenario.

Figure 17 shows the transport demand projections until 2050 for all passenger transport modes. In addition to Figure 16 various additional scenarios are included:

- ‘Klimaschutz’ includes three individual scenario projections which calculate the effect of until end 2012 implemented political measures (AMS 2012 – ‘aktuelle Maßnahmen Szenario’), climate strategy with 80% reduction of GHG-emissions until 2050 (KS 80) and climate strategy with 90% reduction of GHG-emissions until 2050 (KS90).
- ‘Verkehr 2050’ – a scenario which with focus on rising share of electricity produced fuels with two variants: base scenario (‘Basis’) and challenging scenario with reduced demand ‘Ziel’.

- The two scenarios within the Energy concept of the former Government ('Energiekonzept'), scenario 'Reference' and 'Ziel I/IV' project almost identical transport demand until 2050. Therefore, only the scenario 'Ziel I/IV' was selected.
- BMU Leitstudie also is a goal oriented scenario which tries to implement various measures in order to meet the climate policy goals of the government.
- Modell D is a further goal oriented scenario which shows possible ways to match climate policy goals. Both its variants ('Referenz' and 'Innovation') focus on different technical realisations of transport and energy supply, but are based on almost identical demand.
- 'eMobil 2050' shows the two already discussed scenarios 'Grenzenlos' and 'Regional'. As already explained above, these two scenarios vary.

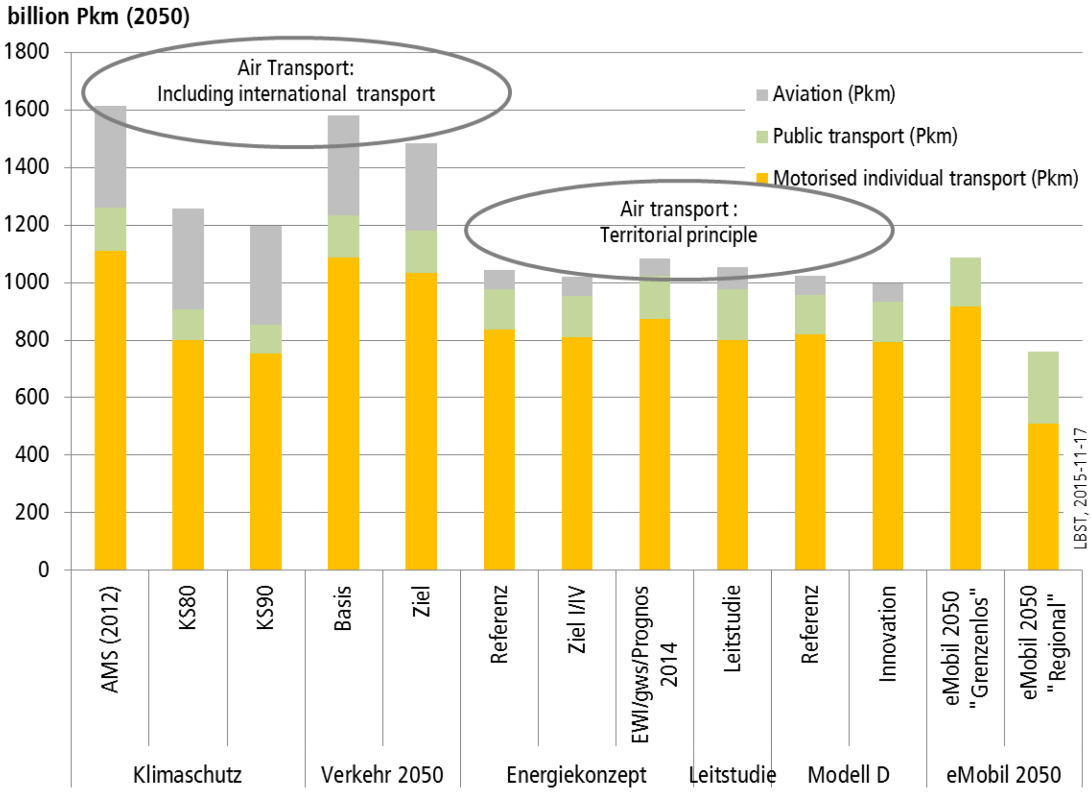


Figure 17: Comparison of passenger transport scenarios for Germany

Passenger air transport is differently calculated in the scenarios, based on different territorial restrictions. Some studies (Energiekonzept, Leitstudie, Modell D) calculate only the air transport demand over the territory of Germany. This includes the inland transport as well as the international transport from German airports to the German boundary. Other studies like 'Klimaschutz' and 'Verkehr 2050' calculate the demand of all departures from Germany until the first destination outside.

The data for 2010 are listed in Table 15.

Table 15: **Different territorial balances for passenger air transport 2010**

	Inland air transport	Air transport over German territory	Total air transport from Germany
Billion passenger kilometres (pkm)	10.7	52.8	194
Source	Verkehr in Zahlen [VIZ 2013/14, p 218]	Verkehr in Zahlen [VIZ 2013/14, p 218]	Verbändestudie [WWF et al. 2014, p 47]

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions from aviation the total passenger transport demand from aviation including international aviation has been taken into account ('Total air transport' in Table 15).

Figure 18 depicts the development of cargo transport demand until 2050.

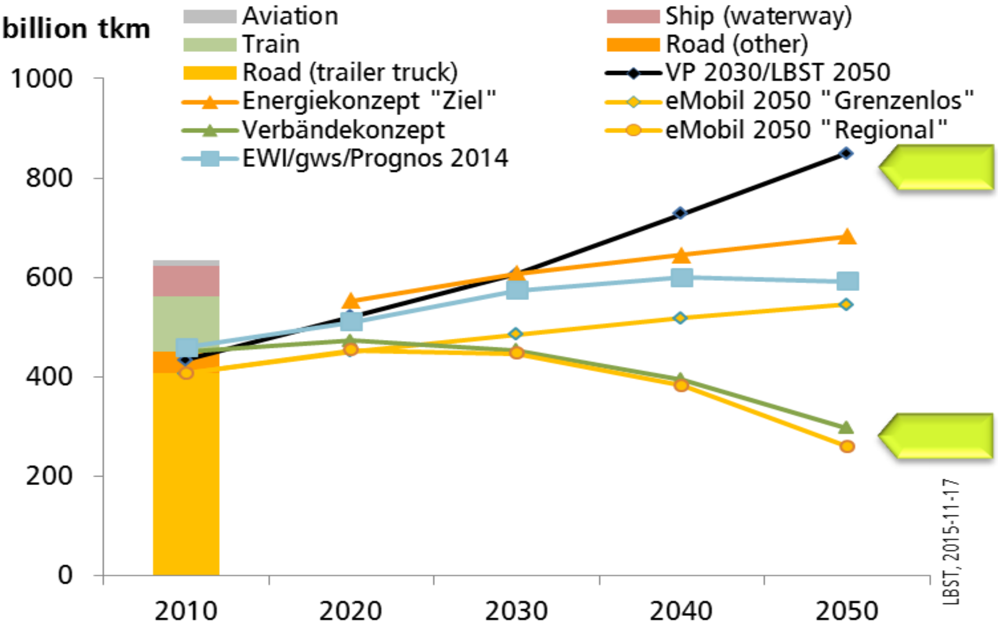


Figure 18: **Exemplary overview over road freight transport scenarios for Germany (arrows = boundary scenarios selected for this study)**

The different bars in Figure 18 represent the individual contributions of different transport modes in 2010:

The **orange bar** shows the cargo transport demand 2010 for trailer truck road transport larger than 12 t total weight. The red bar shows the demand 2010 for other trucks (3.5-12 t total weight). As road transport covers by far the largest share, its development is sketched in the figure for various scenarios:

- Similar to passenger transport modes, the lowest demand is projected in the scenarios 'eMobil 2050 Regional' and 'Verbändekonzept'. Again, this reflects the intention of the scenario goals to match aggressive climate policy goals.
- Scenario 'VP 2030/LBST 2050' is constructed for the present study. It has been assumed that for this scenario the growth from 2010 until 2050 (+96%) for cargo road transport. The previous VP 2025/MKS 2050 with a cargo road transport demand growth of 130% against 2010 [MKS 2014] is seen as highly unrealistic. However, even the VP2030 scenario projection forms a probably unrealistic upper limit which comes close to the scenario 'Verkehr 2050 Basis' (see Figure 19).
- Scenario 'Energiekonzept' 2050 matches the 2030 projection but reduces its growth expectations beyond.
- The scenario 'eMobil 2050 Regional' forms a lower boundary as this projection consequently reduces avoidable transport volumes to meet climate policy goals. This is almost similar to the projection in the 'Verbändekonzept' which follows a similar strategy.
- In between these limits is the scenario 'eMobil 2050 Grenzenlos' which according to the authors intuition sketches the development in an unlimited 'business as usual' scenario.

The **green bar** shows the demand for rail transport. The different scenario projections are compared in Figure 19. Almost all projections considerably increase the share of rail transport, except the bau scenario 'eMobil 2050 Grenzenlos'.

The **purple bar** shows the demand for inland water way transport. The different scenarios vary between a doubling of inland water transport demand and constant demand until 2050.

The small **grey bar** shows the demand for air transport. The transport demand for air freight has an almost negligible share of about 1% which even in 2050 does not increase considerably. In the scenario calculations freight air transport is not included due to its small share.

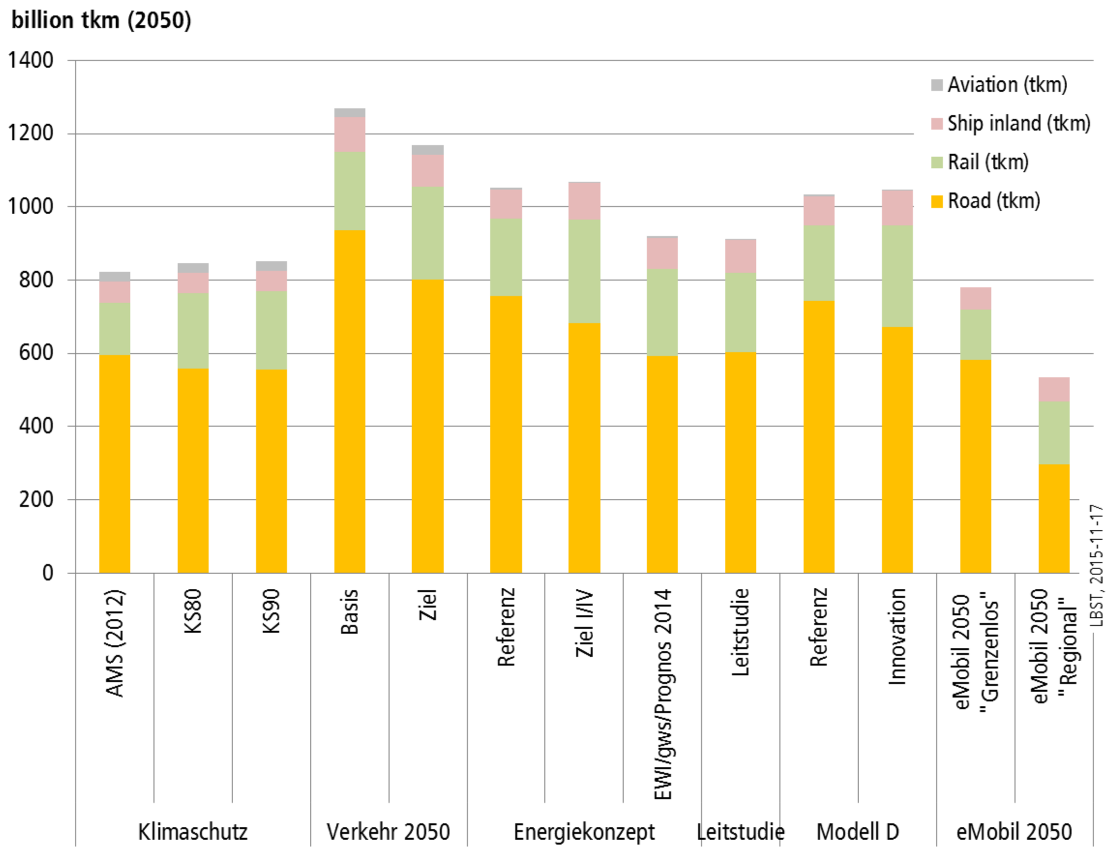


Figure 19: **Comparison of freight transport demand in 2050 according to various studies**

The large green arrows in Figure 16 and Figure 18 mark the two scenarios which are selected as upper and lower boundary scenario. These are:

- eMobil 2050 Regional for the lower low case.
- VP 2030 and its extension to 2050 by LBST for the present context.

As these scenarios partly focus on surface transport only or miss some modal split details which are required for the present context, some further assumptions are made which are explained in Annex 8A1 leading to the selected scenarios for high and low transport demand. Figure 20 and Figure 21show the scenarios for the transport demand used in this study without and including overseas freight transport respectively.

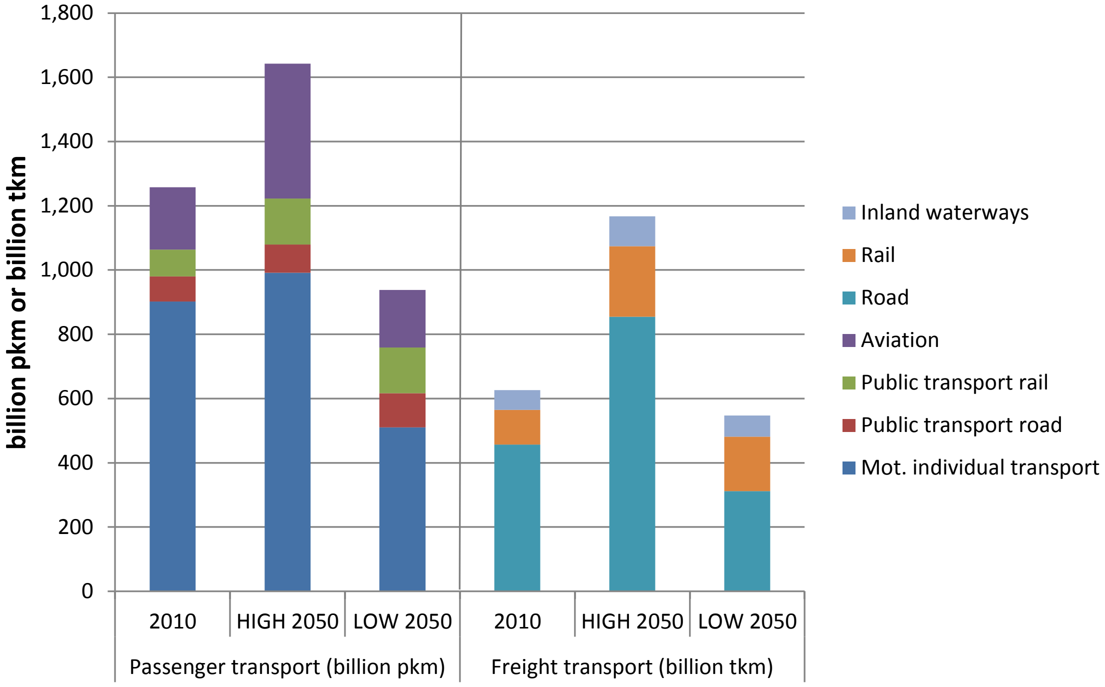


Figure 20: **Scenarios for transport demand used in this study (without overseas freight transport)**

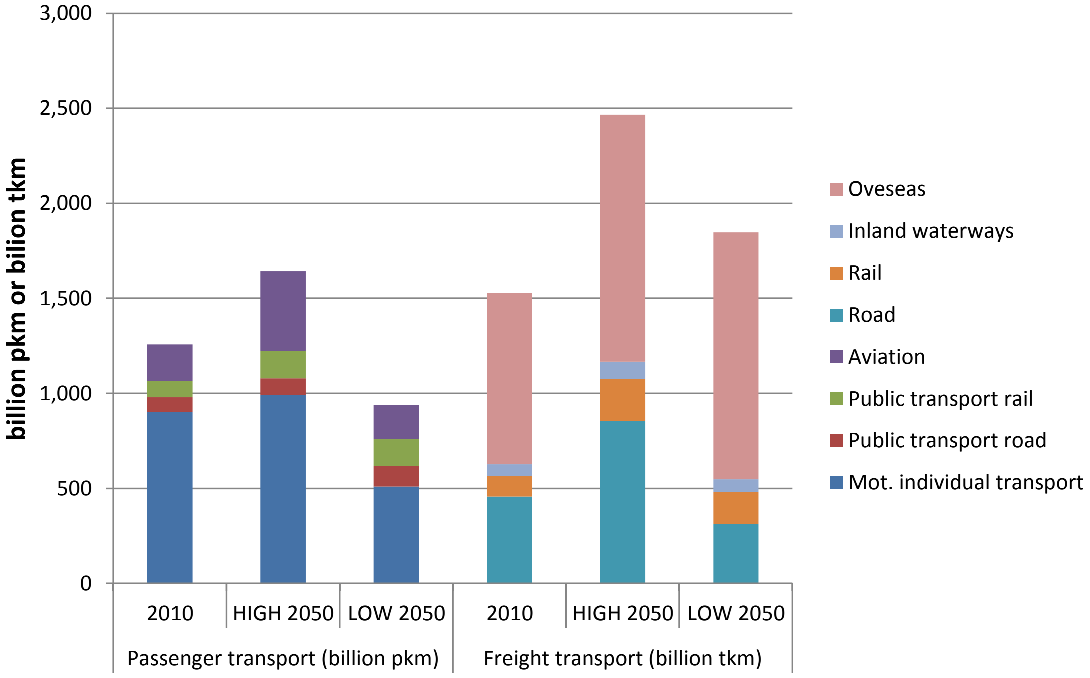


Figure 21: **Scenarios for transport demand used in this study (including overseas freight transport)**

For the calculation of the transportation fuel demand and the associated GHG emissions the overseas transport has been included.

NON-ROAD MOBILE MACHINERY

The category of 'non-road mobile machinery' (NRMM) consists of a wide range of working machines and applications that today are typically powered by internal combustion engines, e.g. agricultural machines, construction equipment, backup power, etc. As NRMM predominantly run on diesel and gasoline but also on LPG and CNG, they share the same fuel basis as road transportation fuels. This makes them difficult to differentiate in fuel statistics and also prone to double-counting.

According to the current review of the EU NRMM directive [EC-NRMM 2014], the regulatory focus for non-road mobile machinery is on criteria pollutant emissions as they today account for some 15% of nitrogen oxide (NOx) and 5% particulate matter (PM) emissions in Europe. Future developments of the NRMM regulatory framework in Europe will likely take up NRMM greenhouse gas emissions.

We have found no indication whatsoever that NRMM are considered in fuels for transportation studies. For the sake of completeness, NRMM fuel demands are included in this study. Given its limited relevance energy-wise and in order to reduce model complexity, it is assumed that fuel demand will not change over time – i.e. market growth may be counter-balanced with increasing fuel efficiency – and that this fuel demand is represented as diesel in the modelling of fuels and emissions.

4.1.2 Europe

Based on the goals of the EC-White Paper 'Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system' [EC 2011], the European Commission commissioned various studies investigating political and technical measures and their potential with respect to the GHG-emission targets.

The EU-Reference scenario 2013 (EU Energy, Transport and GHG emissions: Trends to 2050) published in 2013 set the reference for the development of passenger and freight transport volume. On behalf of the Commission a group of several institutions, led by AEA, created various scenarios (up to twelve) which differentiated individual aspects of political incentives and regulations aimed to develop scenarios and strategies which are compatible with the EU GHG-targets.

Figure 22 exhibits two scenarios for passenger transport volume which are chosen as lower and upper limits for the transport demand. AEA low is scenario set No c-5, while AEA bau covers scenario set No. bau-a.

The inner European demand closely matches the demand assumption as set in the EU-Reference scenario 2013. However, in addition international transport volumes outside European boundaries are included. Concerning passenger transport, the additional transport volume is restricted to aviation transport starting from European destinations to the first destination outside Europe. The bar in 2010 gives the transport volume differentiating various transport modes, while the lines show the development of total passenger transport volume until 2050 according to the chosen scenarios.

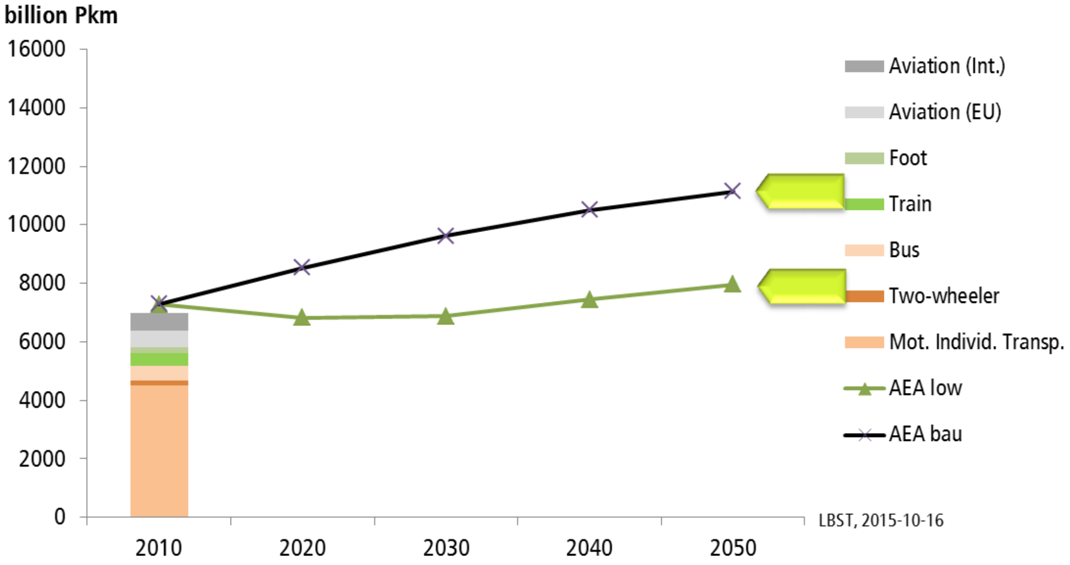


Figure 22: **Overview over passenger transport scenarios for the EU (arrows = boundary scenarios selected for this study)**

Figure 23 gives the corresponding data for the freight transport volume. Also here the inner European transport demand is chosen almost identical to the EU reference scenario 2013. However, the AEA-study group added the international maritime shipping transport volume outside Europe. This, by far more than doubles the total transport demand. And furthermore, the difference between the different scenarios to a large extent is due to different assumptions on overseas transport demand – which is governed by the inner European demand for the corresponding goods.

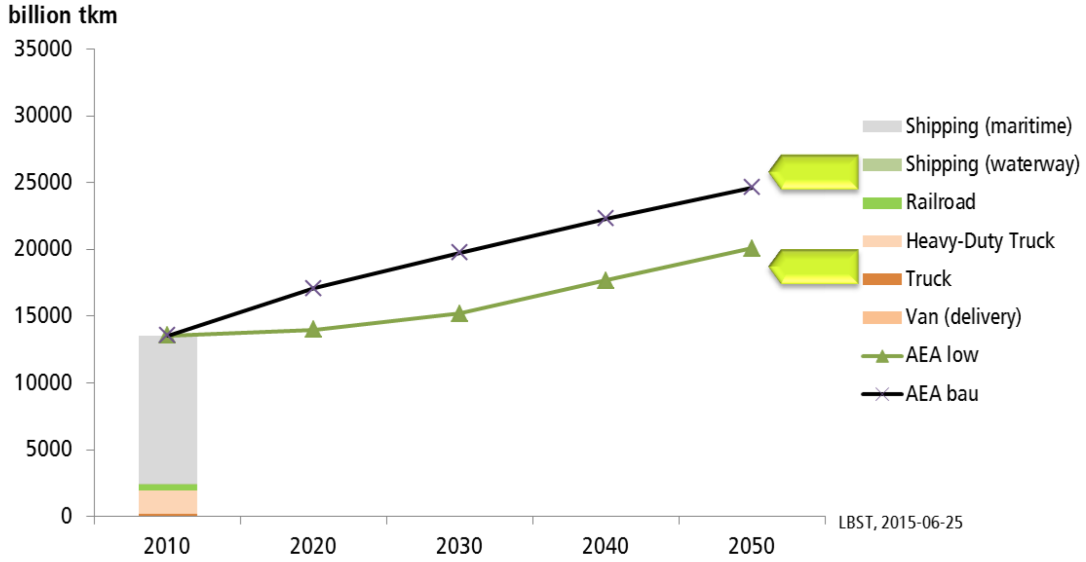


Figure 23: **Overview over freight transport scenarios for the EU (arrows = boundary scenarios selected for this study)**

The transformation of the transport demand into fuel consumption exhibits that the share of the fuel consumption for shipping is much smaller than the corresponding share of the transport demand. Here, differences between the scenarios for inner European fuel strategies and energy saving measures dominate the total energy consumption patterns.

4.1.3 Overview over selected transportation demand scenarios

Table 16 gives an overview over key aspects of the HIGH and LOW demand scenarios selected for this study for Germany and EU-28 respectively.

Table 16: **Key development in the transportation demand scenarios selected for this study**

Transportation demand scenario	Sector	Change from 2010 to 2050	
		DE	EU
HIGH	Passenger	+30% (1)	+50% (3)
	Freight	+60% (1)	+80% (3)
LOW	Passenger	-25% (2)	+10% (4)
	Freight	+20% (2)	+50% (4)

[1] BMVI VP 2030 [BVU et al 2014] / MKS 2050 [MKS 2015]

[2] eMobil 2050 scenario 'Regional' [Hacker et al. 2014]

[3] [AEA 2012] scenario 'BAU-a'

[4] [AEA 2012] scenario 'C5-b'

4.2 Modelling of transportation supply

4.2.1 Methodology and approach

In this chapter it is described how transportation demand and vehicle fleets are modelled. Furthermore, two transportation demand scenarios are selected for Germany and EU-28 each and entered into the model. New vehicles, specific lifetime, average annual driving distances etc. are adjusted to match model results with current transportation statistics.

Figure 24 explains the basic logics of the modelling. The target numbers to be met each year are passenger-kilometer and ton-kilometer.

First, these numbers are translated into vehicle-kilometers, and by means of average driving activity into the number of vehicles. Depending of the average vehicle use the number of new cars is calculated. Here enters the fuel mix of newly registered cars. This guarantees that each year new cars with improved fuel performance are phased in while the age distribution – and therefore the fleet mix of cars of various fuel classes – is properly accounted for during the scenario calculations.

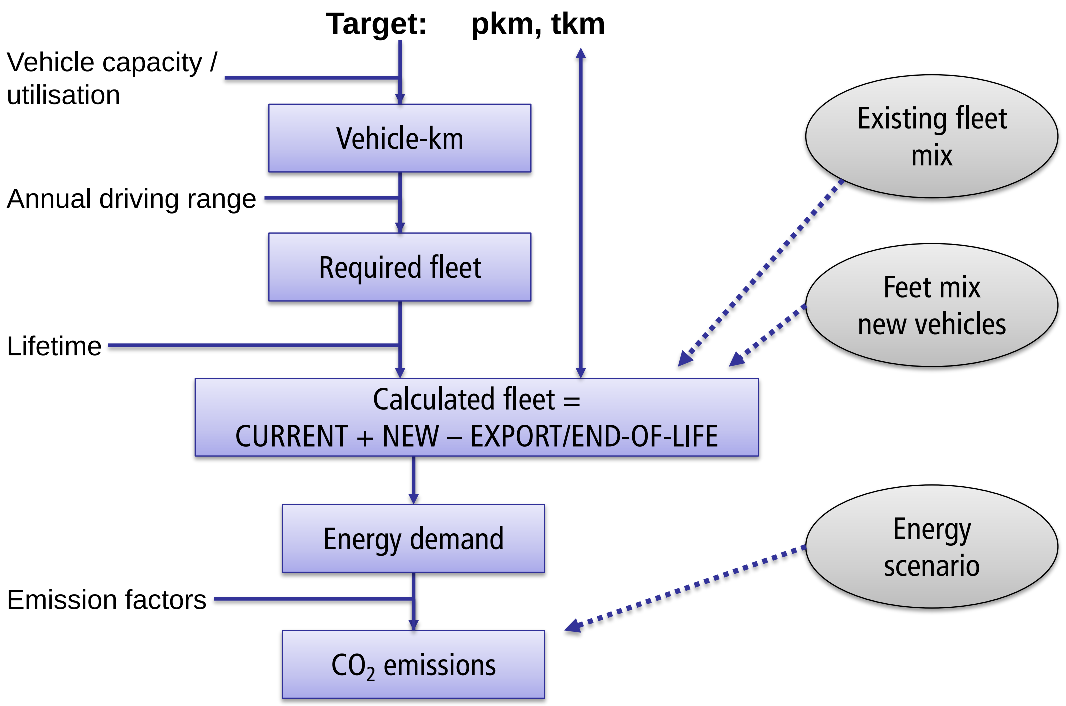


Figure 24: Key parameters and calculation approach in the fleet model

These calculations are performed for each modal mode and, where appropriate, for various vehicle classes within each mode. Due to the disaggregation of data into vehicle numbers and sizes, various parameters must be selected by educated guesses and proper assumptions which are summarized in the next subchapter.

4.2.2 Parameter setting and fleet modelling

Table 17 summarizes the parameter setting for the chosen vehicle-structure for passenger transport. Table 18 is the corresponding equivalent for goods transport. Details are given in Annex C.

Table 17: Parameter setting for passenger transport modes

	Capacity [seats]	Utilisation [%] or occupation [persons/vehicle]	Annual driving range [km/vehicle]	Operation time [yr]
Car		1.5 cap/car	14.000	13.9
Bus		23 cap/car	43,000	14
Short distance train	190	22% (2010) - 30% (2050)	120,000	30
Long-distance-train	430	42% (2010) - 45% (2050)	200,000	25
aircraft	170	80% (2010) - 85% (2050)	2,500,000	15

Table 18: Parameter setting for freight transport modes

	Average load [t/vehicle-train]	Empty trip-km [%]	Annual driving range [km/vehicle]	Operation time [yr]
Trucks <3.5t	0.2	30%	20,000	12
Trucks 3.5-12t	2.7	20%	25,000	15
Trucks >12t	13.5	10%	75,000	10
Train	532	0%	100,000	39
Inland ships	1,290	20%	13,700	60
Sea ships	35,000	40%	145,000	30

The focus of the present study is on the potential or substitution of conventional combustion engines. As road transport has by far the largest share on the transport energy consumption the present parameter setting is more detailed for road transport than for other transport modes. The parameter setting influences the phase-in time of new technologies, and therefore the fuel consumption and GHG-emissions. However, this transformation speed has only a marginal influence for energy consumption and GHG-emissions in the final scenario year 2050. Therefore, the present parameter setting is sufficient. Further disaggregation and detailing will not influence the general outcome from the calculations and the conclusions.

5 IMPROVEMENTS IN POWER-TO-FUEL PATHWAYS AND VEHICLE POWERTRAINS

In this chapter possible technology development for alternative fuels, infrastructure, and powertrains is presented.

On the one hand, conservative assumptions have been applied for the evolution of powertrain efficiency (i.e. the annual decrease of fuel consumption of vehicles). On the other hand, a rapid development of renewable transportation fuels has been assumed in order to achieve a target scenario of 100% renewable energy sources in transportation fuels by 2050.

For the calculation of cost reduction from series production of renewable transportation fuel production facilities a world market has been assumed. Differentiation between different regions would exceed the complexity of the assessment in this study.

5.1 Development of fuel supply pathways

This chapter addresses the following questions with a view to the 2050 scenario target of 100% renewable energies in transportation:

- How may fuel production develop over time, e.g. with regard to energy needs for the production of electricity-based fuels (PtX)?
- How may electricity and transportation fuel production and distribution costs develop over time, considering capacity effects and based on learning-curves?

The following renewable electricity and electricity-based transportation fuel pathways (PtX) have been analysed to this end:

- Power-to-hydrogen (PtH_2) via water electrolysis with renewable electricity
- Power-to-methane ($PtCH_4$) via water electrolysis and subsequent methanation
- Power-to-liquids (PtL: gasoline, kerosene, diesel, methanol)
- Electricity from renewable power plant mix

Fossil fuel references have been assessed, respectively, for a direct comparison with PtX fuel pathways and renewable electricity:

- Hydrogen from steam-methane reforming of natural gas
- Methane from natural gas
- Liquid fuels from crude-oil

5.1.1 Hydrogen from natural gas steam reforming (fossil reference)

As fossil reference hydrogen from onsite natural gas steam reforming has been assumed. The supply of natural gas follows the assumptions made for CNG above. The technical data for the onsite steam reforming plant are based on data supplied by H2Gen [H2Gen 2002], [H2Gen 2007]. The economic data are based on data supplied by [Schnell 2008].

Table 19: Onsite steam methane reforming

	Unit	2015	2020 and later
Capacity	Nm^3_{H2}/h	100	100
	$kW_{H2,\ LHV}$	300	300
Purity	-	>99.999%	>99.999%
H_2 pressure	MPa	0.9	0.9
Natural gas consumption (LHV)	$kWh/kWh_{H2,\ LHV}$	1.45	1.45
Electricity consumption	$kWh/kWh_{H2,\ LHV}$	0.094	0.094
Economic data			
Investment	€	1,300,000	650,000
Lifetime	yr	15	15
Equivalent full load period	h/yr	6,000	6,000
Maintenance and repair	€/yr	96,000	32,500

The steam methane reformer supplies hydrogen at a pressure of 0.9 MPa. The hydrogen produced is compressed to 30 MPa and stored in bundles of cylinders or tanks. For the filling of high-pressure hydrogen buffer storage and vehicles, the hydrogen is compressed to about 90 MPa (for passenger cars). In this context, temperature increases during rapid refuelling have to be taken into account to ensure a pressure level of 70 MPa at 15°C in a fully fuelled vehicle tank.

The electricity requirement of the refueling station consists of the electricity requirement for hydrogen compression and the electricity requirement for hydrogen pre-cooling. The electricity requirement for hydrogen compression amounts to about 0.12 kWh per kWh of hydrogen. The electricity requirement for pre-cooling amounts to about 0.19 kWh per kWh of hydrogen in 2015 which decreases to about 0.09 kWh per kWh of hydrogen in 2020 and 0.012 kWh per kWh of hydrogen in 2030 (see chapter 5.1.2).

For the combination of hydrogen production on-site via steam methane reforming, the stationary hydrogen storage at the refuelling station was assumed to equal 40% of the average daily turnover.

Table 20: **CGH_2 refuelling station for H_2 generation onsite via steam methane reforming (reference)**

	2015	2020	2030	2040	2050
Number of dispensers	1	1	1	1	1
CGH_2 output	120 t/a	120 t/a	120 t/a	120 t/a	120 t/a
Investment (€)					
H_2 storage (30 MPa)	84,640	84,640	84,640	84,640	84,640
H_2 high pressure buffer	52,000	28,273	24,383	21,227	18,479
Primary compressor	124,342	67,607	58,304	50,758	44,188
Secondary compressor	327,466	178,050	153,547	133,675	116,372
Pre-cooling	130,000	70,684	60,956	53,067	46,198
Dispenser	103,802	56,440	48,672	42,373	36,888
Software for dispenser	22,231	12,087	10,424	9,075	7,900
Piping	3,762	3,762	3,762	3,762	3,762
Safety inspection	12,650	12,650	12,650	12,650	12,650
Installation	6,353	6,353	6,353	6,353	6,353
Approval	35,000	35,000	35,000	35,000	35,000
Total	902,246	555,545	498,690	452,578	412,429
Operating and maintenance (€/a)					
Safety inspection pressure vessels	2,880	2,880	2,880	2,880	2,880
Dispenser calibration	716	716	716	716	716
Maintenance compressors	22,258	12,102	10,437	9,086	7,910
Total	25,854	15,698	14,033	12,682	11,506

5.1.2 Hydrogen from renewable electricity

5.1.2.1 Hydrogen generation

Hydrogen is generated via water electrolysis. There are alkaline electrolysers, electrolysis applying proton exchange membranes (PEM electrolyser), and electrolysers using an ion-conducting solid oxide (SOEC). Alkaline and PEM electrolysers are operated at 50 to 80°C (low temperature electrolysis). SOEC are operated at temperatures up to 1000°C (high temperature electrolysis). Table 21 shows the characteristics of various electrolyser types.

Table 21: **Characteristics of various electrolyser types**

	Alkaline electrolysis	PEM electrolysis	SOEC
Cathode reaction	$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$	$2\ H^+ + 2\ e^- \rightarrow H_2^-$	$H_2O + 2\ e^- \rightarrow H_2^- + O^{2-}$
Anode reaction	$2\ OH^- \rightarrow 0.5\ O_2 + H_2O + 2\ e^-$	$H_2O \rightarrow 0.5\ O_2 + 2\ H^+ + 2\ e^-$	$O^{2-} \rightarrow 0.5\ O_2 + 2\ e^-$
Overall reaction	$H_2O \rightarrow H_2 + 0.5\ O_2$	$H_2O \rightarrow H_2 + 0.5\ O_2$	$H_2O \rightarrow H_2 + 0.5\ O_2$
Electrolyte	KOH	H^+ conducting polymer	O^{2-} conducting ceramic
Electrodes	Ni	$Pt/C/IrO_2$	Ni, ceramic
Temperature	50-80°C	50-80°C	700-1000°C

Alkaline and PEM electrolysers are commercially available. SOEC are still in the state of research and development.

Low temperature electrolysis (alkaline, PEM) has been applied for the supply of compressed gaseous hydrogen (CGH_2) for hydrogen fuelled vehicles. For the supply of synthetic methane (chapter 5.1.4) and synthetic liquid fuels (chapter 5.1.5) low temperature and high temperature electrolysis has been taken into account.

The electricity consumption of the alkaline electrolysis plants from the Canadian company Hydrogenics amounts to about 5.2 kWh per Nm^3 of hydrogen including all auxiliaries (AC/DC inverter, pumps, blowers, hydrogen purification system, etc.). Based on the lower heating value (LHV) the efficiency amounts to about 58%. One electrolyser unit can be operated between 40 and 100% of full load capacity. The pressure of the delivered hydrogen amounts to 1.1 MPa (absolute) [Hydrogenics 2011]. A hydrogen purity of 99.999% can be achieved to meet the SAE J2719 fuel specifications for fuel cell vehicles. Since several electrolyser units are generally used the operating range is 10 to 100% of full load capacity [Hydrogenics 2013]. Hydrogenics has manufacturing facilities in Belgium and Germany.

The efficiency including all auxiliaries generally does not change with capacity if the same pressure level and hydrogen purity should be achieved. Today, the efficiency of larger electrolysis plants (5 MW_e) also amounts to about 68% and 69% based on the higher heating value (HHV) for alkaline and proton exchange membrane (PEM) electrolysers respectively [DLR et al 2015]. Based on the lower heating value (LHV) the efficiency would be about 57.5% (alkaline electrolysis) and 58.4% (PEM electrolysis).

In the future, a decrease of electricity consumption can be expected. According to [E4tech et al 2014] an electricity consumption of 50 kWh per kg of hydrogen can be expected for 2030 in case of alkaline electrolysers and 47 kWh per kg of hydrogen in case of PEM electrolysers, leading to an efficiency of about 67% and about 71% respectively based on the LHV. According to [DLR et al 2015] an efficiency of about 84% at rated load referred to the HHV can be expected in the future leading to about 71% referred to the LHV.

In this study a full market penetration of PEM electrolysers has been assumed until 2040.

Table 22 shows the evolution of electricity consumption and efficiency for low temperature water electrolysis.

Table 22: Evolution of electricity consumption and efficiency for low temperature water electrolysis

	Unit	2015	2020	2030	2040	2050
Electricity consumption	kWh/Nm³	5.2	4.6	4.5	4.2	4.2
	kWh/kg	58	51	50	47	47
	kWh/kWh_{LHV}	1.733	1.538	1.500	1.410	1.410
Efficiency (LHV)		57.7%	65.0%	66.7%	70.9%	70.9%

For the calculation of the specific investment for electrolysers cost reduction from series production has been considered via a learning curve. It has been assumed that the cumulative worldwide installed capacity increases from about 1 GW today (2015) to about 1000 GW in 2050. The installed capacity follows a logistic curve based on the following equation:

$$f(t) = G \cdot \frac{1}{1 + e^{-k \cdot G \cdot t}\left(\frac{G}{f(0)} - 1\right)}$$

with

G	cumulative final capacity
t	time (1..nth year)
f(t)	installed capacity at t
k	Constant

Figure 25 shows the evolution of the worldwide cumulative installed electrolysis capacity.

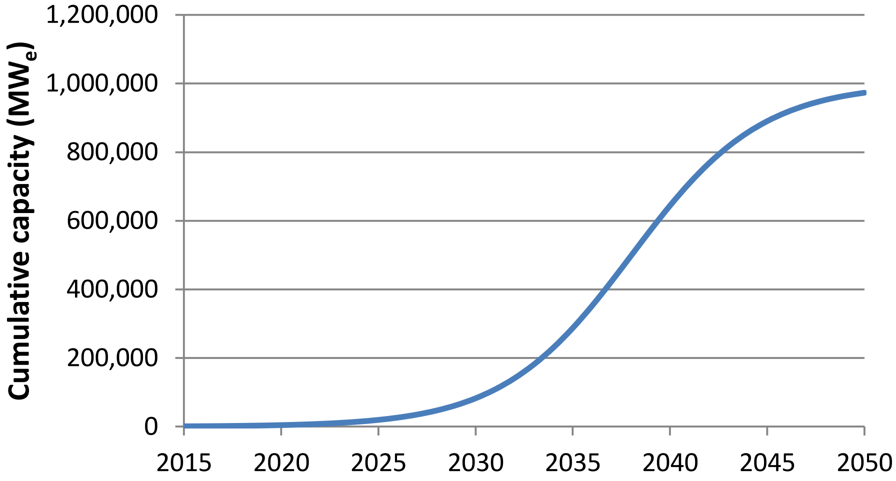


Figure 25: Cumulative installed electrolysis capacity

There is a trade-off between low investment and high efficiency. Lower current density leads to a high efficiency and to a high investment because of higher required cell area. In [Sterner 2014] the progress ratio for power-to-gas (PtG) plants is indicated with 0.87. The major fraction of the investment of PtG plants consist of the investment for the electrolysis plant. Therefore, for electrolysis it has been assumed that the progress ratio also amounts to 0.87. This means that every doubling of installed cumulative capacity leads to a cost decrease of 13%. In this study a PR of 0.87 has been applied generally for low temperature electrolysis (both for alkaline and PEM electrolysis). The specific investment at year t can be calculated by:

$$I_{p(n)} = I_{P(0)} \cdot \left(\frac{P(n)}{P(0)} \right)^{\frac{\ln(PR)}{\ln(2)}}$$

with

$I_{P(n)}$ Investment in year n
$I_{P(0)}$ Investment today (2015)
P(n) Capacity in year n
P(0) Capacity today (2015)

The specific investment for electrolysis plants including all auxiliaries and the building with a capacity of 1 to 2 MW_e[5] amounts to about 2900 € per kW of electric power input based on quotations of manufacturers and own estimates for the cost of the building. A 2 MW_e plant consists of 6 electrolyser units (Figure 26). The footprint of this 2 MW_e plant amounts to 667 m². According to [DLR et al 2015] the cost of the building amounts to 1375 € per m² leading to about 920,000 € for the 2 MW_e plant.

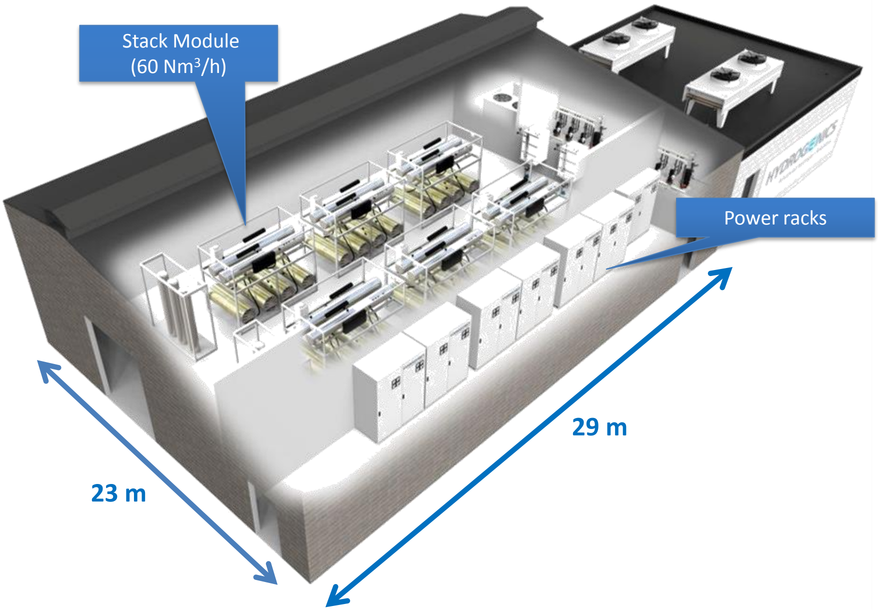


Figure 26: **Alkaline electrolysis plant, 360 Nm³/h capacity, electricity input of ~2 MW [Hydrogenics 2012], [Hydrogenics 2013]**

In 2015 the specific investment for alkaline electrolysis plants with a capacity of approximately 5 MW_e[6] including all auxiliaries and the building amounts to about 1300 € per kW of electric power input based on manufacturer data and data in [DLR et al 2015].

Manufactures who offer larger PEM electrolysers are Siemens and Proton Energy Systems (Proton onsite, model M1 and M2). The Siemens SILYZER 200 generates 225 Nm³ H_2 of hydrogen per hour and unit at a purity of 99.5 to 99.9% with a rated electricity input of 1.25 MW leading to an efficiency of about 54% based on the LHV [Siemens 1/2015],

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[5] Rounded number, the electricity consumption of 5.2 kWh/Nm³ and a H_2 production capacity of 360 Nm³/h leads to 1.872 MW_e

[6] Rounded number, efficiency of 58% (LHV) and a H_2 production capacity of 1000 Nm³/h (3 MW H_2) leads to 5.17 MW_e

[Siemens 2/2015]. The overall efficiency is indicated with 65 to 70% depending on the load probably referred to the HHV leading to about 55 to 59% referred to the LHV. For higher purity (>99.999%) a DeOxo drier is required which lowers the efficiency to about 53 to 57%.

In [DLR et al 2015] the efficiency of the PEM electrolysis plant with a rated electricity input of 5 MW_e is indicated with 58%. The specific investment including all auxiliaries and the building is estimated at about 1000 € per kW of electric power input which is lower than that of the alkaline electrolysis plant. One reason for the lower investment is the lower footprint of PEM electrolysis plant leading to lower cost for the building. The efficiency of the 100 MW_e PEM electrolysis plant is indicated with about 71%. The investment amounts to about 400 € per kW of electric power input. But the 100 MW_e PEM electrolysis plant is not available until 2030.

The specific cost of the building amounts to 253 € per kW_e in case of the 5 MW_e plant and about 490 € in case of the 2 MW_e plant if alkaline electrolysis technology is applied. PEM electrolyser require lower investment for the building (75 €/kW_e instead of 253 €/kW_e in case of the 5 MW_e plant).

On the other hand, larger cell area and higher current density also lead to a decrease of the footprint of alkaline electrolysers. According to [DLR et al 2015] in case of an alkaline 100 MW_e electrolysis plant where cells with a larger cell area has been employed the specific investment for the building decreases to about 84 €/kW_e. Therefore, it can be expected that the cost of the building per unit of capacity also will decrease in the future for alkaline electrolysis plants. The cost data for the 100 MW_e alkaline electrolyses plant indicated in [DLR et al 2015] are related to advanced technology which is not available until 2030.

In this study it has not been distinguished between alkaline and PEM electrolysis. It has been started with the specific investment of today’s alkaline electrolysis plants to model the learning curve until 2050. Figure 27 and Table 23 shows the evolution of the specific investment for low temperature electrolysis for 1 MW_e, 5 MW_e, and 100 MW_e including all auxiliaries and the building. The 100 MW_e is not available until 2030.

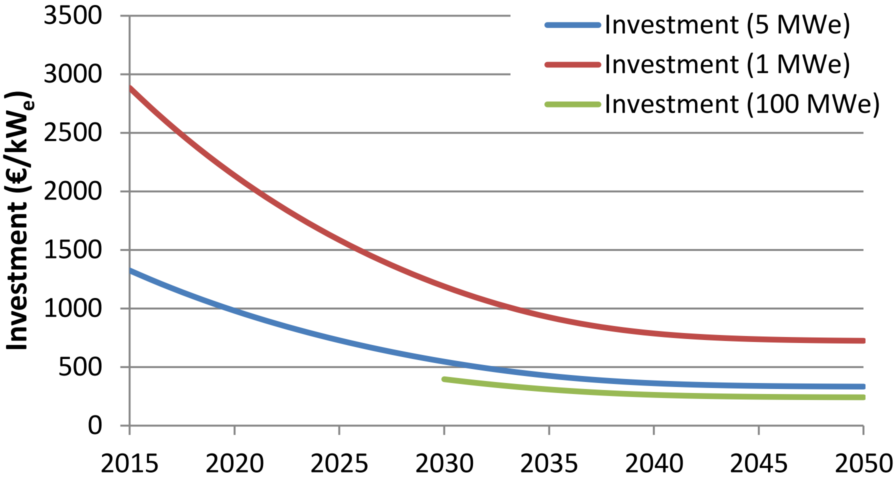


Figure 27: **Evolution of specific investment for low temperature electrolysis**

Table 23: **Specific investment for low temperature water electrolysis**

	Unit	2015	2020	2030	2040	2050
100 MW$_e$	€/kW$_e$	-	-	395	262	241
	€/kW$_{H2, LHV}$	-	-	593	369	340
5 MW$_e$	€/kW$_e$	1324	980	545	361	332
	€/kW$_{H2, LHV}$	2283	1508	818	509	469
1 MW$_e$	€/kW$_e$	2883	2135	1188	786	724
	€/kW$_{H2, LHV}$	4998	3284	1782	1109	1020

A lower investment for the 1 MW$_e$ plant for onsite hydrogen generation than that presented in Table 23 and Figure 27 is imaginable in the future. Therefore, the specific investment for onsite hydrogen generation can be considered as conservative.

The equivalent full load period is assumed to be 4000 h per year leading to a rated power of about 1.73 MW$_e$ for a hydrogen refuelling station with an average hydrogen output of about 330 kg per day and an electricity consumption of 5.2 kWh/Nm³ of hydrogen. In [Hydrogenics 2013] a refuelling station with a maximum output of 765 kg of hydrogen per day (average ~350 kg/d) with onsite hydrogen generation is described using the same electrolysis plant as shown in Figure 26. Therefore, for onsite hydrogen production the specific cost data for the 1-2 MW$_e$ electrolysis plant has been used.

The costs of operating and maintenance including stack replacement for the 5 MW$_e$ plant and for an equivalent full load period of 8000 h per year amount to about 350,000 € per year leading to about 7% of investment excluding building per year [DLR et al 2015]. In this study an equivalent full load period of 4000 h has been assumed leading to operating and maintenance costs of about 3.5% of investment excluding building per year.

It has been assumed that for the electrolysis plant for hydrogen generation the hydrogen refuelling station the specific operating and maintenance costs are the same as for the larger (5 MW_e) plant.

5.1.2.2 CGH_2 refueling station

The hydrogen refueling station is designed for the refuelling of hydrogen vehicles with 70 MPa vehicle tanks.

For 2015 the electricity consumption for the hydrogen refueling station has been derived from [Hydrogenics 2013]. In [Hydrogenics 2013] the electricity consumption for the supply of CGH_2 at 70 MPa including electrolysis, hydrogen compression, pre-cooling and dispensing is indicated with 68 kWh per kg of CGH_2 (2.04 kWh of electricity per kWh of CGH_2 based on the LHV). The electrolysis plant alone consumes about 1.73 kWh per kWh of hydrogen. As a result about 0.31 kWh per kWh are required for compression and pre-cooling. If the hydrogen compression required about 0.12 kWh per kWh of CGH_2 the electricity requirement for pre-cooling would amount to 0.19 kWh per kWh of CGH_2.

Until now the pre-cooling equipment is not optimized towards low electricity consumption. According to [Kampitsch 2012] the electricity requirement amounts to about 2 kWh per kg of hydrogen from idle plus 1 kWh per kg of hydrogen during vehicle refueling. For 2020 the electricity consumption for pre-cooling is assumed to be 3 kWh per kg of hydrogen or about 0.09 kWh per kWh of hydrogen referred to the LHV as indicated in [Kampitsch 2012].

According to [Elgowainy & Reddi] the electricity consumption for pre-cooling in a well utilized hydrogen refueling station can be lowered to less than 1 kWh per kg of hydrogen. The electricity consumption for pre-cooling can be calculated by:

$$W_{el} \approx \frac{0.3 + \frac{54}{Daily\ dispensed\ kg_{H2}}}{COP}$$

COP = Coefficient of Performance

At an ambient temperature of 15°C (average temperature on earth) the COP amounts to about 1.2. If 300 kg of hydrogen were dispensed per day the electricity consumption for pre-cooling would amount to 0.4 kWh per kg of hydrogen or about 0.012 kWh per kWh of hydrogen referred to the LHV. This value has been used for 2030 and later.

The economic data for the refueling stations are shown in Table 24 if the hydrogen is supplied via onsite water electrolysis. The economic data are based on information from [Adler 2001], [Adler 2005], [Phaedrus 2013], [Hendrickx 2015], and quotations from manufacturers.

Table 24: **CGH_2 refuelling station with onsite hydrogen generation via water electrolysis**

	2015	2020	2030	2040	2050
Number of dispensers	1	1	1	1	1
CGH_2 output	120 t/a	120 t/a	120 t/a	120 t/a	120 t/a
Investment (€)					
H_2 storage (30 MPa)	201,020	201,020	201,020	201,020	201,020
H_2 high pressure buffer	52,000	28,273	24,383	21,227	18,479
Primary compressor	165,152	89,796	77,439	67,416	58,690
Secondary compressor	327,466	178,050	153,547	133,675	116,372
Pre-cooling	130,000	70,684	60,956	53,067	46,198
Dispenser	103,802	56,440	48,672	42,373	36,888
Software for dispenser	22,231	12,087	10,424	9,075	7,900
Piping	3,762	3,762	3,762	3,762	3,762
Safety inspection	12,650	12,650	12,650	12,650	12,650
Installation	6,353	6,353	6,353	6,353	6,353
Approval	35,000	35,000	35,000	35,000	35,000
Total	1,059,435	694,114	634,205	585,617	543,311
Operating and maintenance (€/a)					
Safety inspection pressure vessels	6,840	6,840	6,840	6,840	6,840
Dispenser calibration	716	716	716	716	716
Maintenance compressors	26,339	14,321	12,350	10,752	9,360
Total	33,895	21,877	19,906	18,308	16,916

In case of hydrogen from water electrolysis using renewable electricity the hydrogen storage is assumed to be 100% of the average daily hydrogen output.

5.1.3 CNG and LNG from natural gas (fossil reference)

The energy requirement and GHG emissions for the supply of CNG from imported natural gas (pipeline 4000 km) and LNG from imported LNG (distance 5,500 nautical miles) have been derived from [JEC 2014] (except the GWP factors where AR5 instead of AR4 has been applied).

Table 25: Greenhouse gas emissions and energy use for the supply and use of CNG and LNG

	CNG	LNG
GHG emissions (g CO2 equivalent/MJ)		
WTT	17.1	20.4
TTW	55.1	55.0
Total	72.2	75.4
Energy loss (MJ/MJ)		
WTT	0.21	0.22
TTW	1.00	1.00
Total	1.21	1.22

The price for piped natural gas has been derived from the crude oil price by multiplication with 0.80 as indicated in [JEC 2007] leading to the NG price shown in Table 26.

Table 26: Crude oil price and resulting price for gasoline and diesel

		2015	2020	2030	2040	2050
Crude oil price	US$/bbl	60	105	102	100	100
	€/bbl	54	79	77	75	75
	€/kWh	0.034	0.050	0.048	0.047	0.047
	€/GJ	9.4	13.8	13.4	13.1	13.1
NG price	€/kWh	0.027	0.040	0.038	0.038	0.038
	€/GJ	7.5	11.0	10.7	10.5	10.5

The exchange rate for 2015 has been assumed to be 0.8953 €/US$ (average exchange rate in May 2015). For 2020 and later the exchange rate has been assumed to be 0.75 €/US$.

The cost for distribution (0.0064 €/kWh or 1.8 €/GJ respectively) and the CNG refueling station has been added.

Table 27: CNG refuelling station

	Unit	Value	Reference/comment
Number of dispensers	-	1	
CNG output	t/a	440	
	million kWh/a	6.1	
Electricity consumption	kWh/kWh$_{CNG}$	0.022	[JEC 2014]
Investment			
Dispenser	€	30,500	[Landinger 2002]
CH_4 storage (3-bank system)	€	50,000	[Pütz 2002]
Compressor	€	48,800	[Landinger 2002]
Building	€	20,000	[Pütz 2002]
Approval	€	35,000	[Hendrickx 2015]
Installation	€	14,930	*
Total	€	199,230	
Maintenance, repair, other			
Maintenance and repair	€/a	4,480	10% of investment compressor/a
Recurring Saftey inspection	€/a	1,440	48 bottles, 150 €/(bottle* 5a
Dispenser calibration	€/a	716	[Hansen 1998]

* LBST estimate: 10% of the component costs

For LNG it has been assumed that the LNG is imported from Qatar. The price for natural gas at the natural gas field (where the large natural gas liquefaction plant is located) has been derived from the crude oil price by multiplication with 0.44 as indicated in [JEC 2007].

Table 28: Natural gas liquefaction plant

	Unit	Value	Reference
Capacity	MW$_{LNG}$	12,500	[Bauer & Schmittinger 1996]
Equivalent full load period	h/a	8000	
Electricity consumption	kWh/kWh$_{LNG}$	0.036	[Bauer & Schmittinger 1996]
Natural gas losses	kWh/kWh$_{LNG}$	0.013	[Bauer & Schmittinger 1996], [Masake 1997]
Investment	million €	2,500	[Bauer & Schmittinger 1996]
Lifetime	a	25	
Maintenance and repair	-	4% of investment/yr	

The electricity demand is met by a combined cycle gas turbine (CCGT) power plant with an efficiency of 58.1%.

The LNG is transported from Qatar to the EU via ship over a distance of 13,290 km (one way). Within the EU the LNG is transported to the LNG refueling stations via truck over a distance of 500 km (one way).

LNG is mainly proposed as alternative fuel for heavy trucks. The LNG refuelling station is designed for the refueling of heavy trucks. The LNG refueling station also consists of components for CNG dispensing for boil-off use.

Table 29: LNG refuelling station

	Unit	Value	Reference/comment
Number of dispensers	-	2	
LNG output	t/a	5125	
	million kWh/a	71	
Electricity consumption	kWh/kWh_{CNG}	0.000055	[Kesten 1998]
Investment			
Dispenser	€	189,000	[Hendrickx 2015]
LNG tank	€	145,000	[Hendrickx 2015]
Cryo pump incl. valves and controller	€	129,000	[Hendrickx 2015]
CH_4 storage	€	20,000	[Hendrickx 2015]
Compressor	€	25,000	[Hendrickx 2015]
Equipment for odorisation of boil-off	€	26,000	[Hendrickx 2015]
Civil work (roof, pay system)	€	400,000	[Hendrickx 2015]
Approval	€	35,000	[Hendrickx 2015]
Total	€	969,000	[Hendrickx 2015]
Maintenance, repair, other			
Maintenance and repair	€/a	20,050	[Hendrickx 2015]
Spare parts	€/a	4,000	[Hendrickx 2015]
N_2	€/a	5,200	[Hendrickx 2015]
Dispenser calibration	€/a	1,432	[Hansen 1998]

5.1.4 Methane (CNG, LNG) from renewable electricity

In this pathway, renewable methane is produced from hydrogen via water electrolysis with electricity from renewable energy sources and subsequent methanation with CO_2. The renewable methane is dispensed as compressed (synthetic) natural gas (CNG) and liquefied (synthetic) natural gas (LNG).

5.1.4.1 Hydrogen generation

Hydrogen is generated via water electrolysis (see chapter 5.1.2.1). For pathways involving power-to-methane and power-to-liquid the specific data for the larger electrolysis plants (5 MW_e and 100 MW_e) has been used. Further, a variant using solid oxide electrolysis cells (SOEC) has been considered.

SOEC offer the advantage that a part of the energy requirement can be met by heat. The electricity requirement for the splitting of steam is lower than that of liquid water (Figure 28).

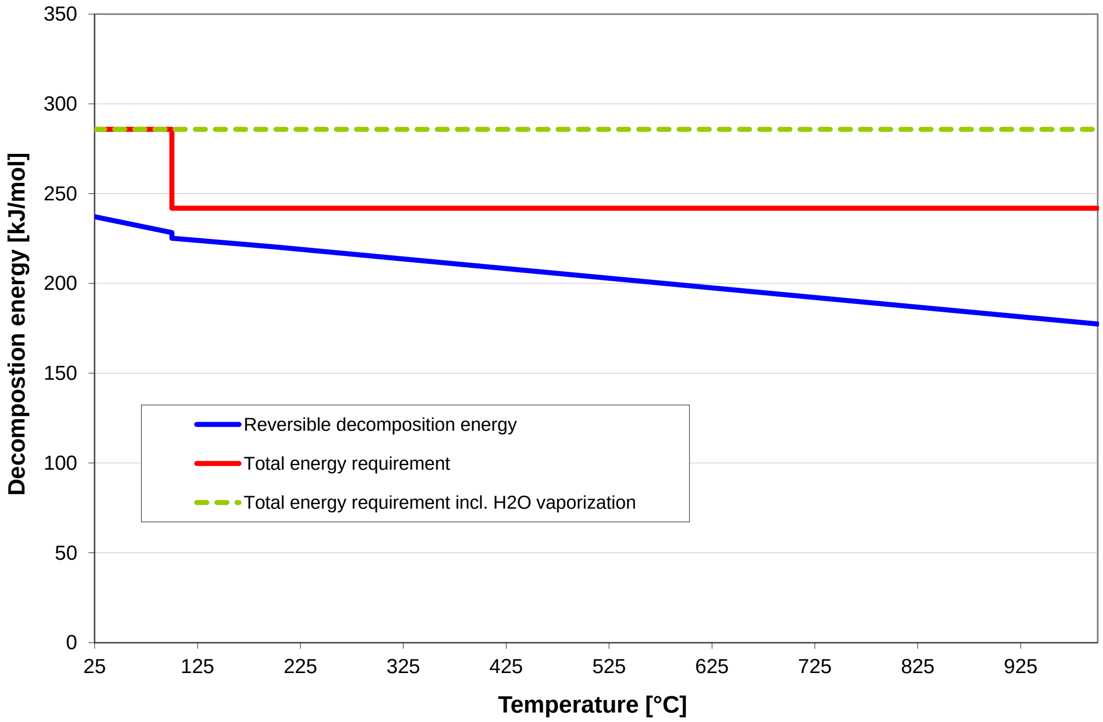


Figure 28: **Theoretical energy demand for water electrolysis**

SOEC are still in the research and development stage. The Danish Partnership for Hydrogen and Fuel Cells [DPHFC 2012] has created a roadmap for steam electrolysis based on SOEC. The investment for the time horizon 2015 to 2017 is indicated with 55,000 kr/(Nm³/h) and for the time horizon 2018 to 2020 with about 20,000 kr/(Nm³/h). The lifetime is indicated with 5 years for 2015 to 2017 and 10 years for 2018 to 2020.

For years 2030 and later for the investment indicated in [DPHFC 2012] a learning curve has been applied using a progress ratio of 0.87. For the years 2030 and later a lifetime of 25 years has been assumed.

Table 30: SOEC energy efficiency, lifetime and investment

	Unit	2015	2020	2030	2040	2050
Electricity consumption*	kWh_{DC}/Nm^3	3.3	3.3	3.2	3.2	3.2
	kWh_{AC}/Nm^3	3.438	3.438	3.333	3.333	3.333
Lifetime	yr	5**	10**	25	25	25
Investment	€/(Nm^3/h)	7400**	2700**	1500	990	910

* Without heat for steam generation; ** [DPHFC 2012]

The methanation is exothermal. If high temperature electrolysis with solid oxide electrolysis cells (SOEC) is used the heat released by the methanation step (200-400°C) can be used to generate steam for the electrolysis. The electrolysis of steam requires less electricity than the electrolysis of liquid water.

5.1.4.2 Methanation

A hydrogen buffer storage with a capacity of 2 h of full load hydrogen production is installed downstream the electrolysis to bridge the limited dynamics of the methanation plant. The hydrogen buffer storage consists of underground steel tubes as used today for natural gas storage. The economic and technical data for the underground steel tubes have been derived from [Jauslin Stebler 2013]. Table 31 shows the technical and economic data of an underground gas storage system in Urdorf in Switzerland.

Table 31: Underground gas storage Urdorf in Switzerland

Parameter	Value
Maximum pressure	10 MPa
Minimum pressure	0.7 MPa
Inner tube diameter	1.485 m
Number of steel tube strings	20
Length of a single steel tube string	202-212 m
Length tubes total	4140 m
Geometric volume	7170 m^3
Investment	16.5 million CHF (12.4 million €)

For lower hydrogen storage capacity demand less steel tube length is required. Therefore, the investment for the hydrogen storage can be scaled linearly.

The next step is methanation with CO_2. The following reaction describes the conversion of hydrogen to methane:

$$4 H_2 + CO_2 \rightarrow CH_4 + 2 H_2O \text{ (gaseous)} \qquad \Delta H = -165 \text{ kJ}$$

The reaction is exothermal. About 83% of the LHV of the hydrogen ends up in the methane. The rest is released as heat. Catalytic methanation is carried out temperatures between 200 and 400°C. Catalysts include Ni or Ru, Rh, Pt, Fe, and Co [Lehner 2012]. Catalytic methanation is carried out at 0.5 MPa pressure.

[Breyer et al 2011] specify an investment of 400 €/kW for methanation referring to the electrical power consumption of the electrolyser producing hydrogen for methanation. [Breyer et al 2011] further assume an electrolysis electricity consumption of 1.65 kWh in reference to the lower heating value of methane. For the methanation plant, this results in an investment of approximately 660 € per kW of methane in reference to the lower heating value (LHV). Costs for maintenance and repair are reported to amount to 2% of the investment.

It has been assumed that as base case the CO_2 is extracted from ambient air. CO_2 extraction from ambient air is carried out in a scrubbing process with sodium hydroxide solution (NaOH) and subsequent regeneration of the scrubbing agent via electrodialysis (see chapter 5.1.7). The electricity consumption for the process comes to 8.2 MJ/kg CO_2 [Sterner 2009].

If the temperature swing adsorption technology developed by Climeworks were applied the electricity consumption for CO_2 extraction from air amounts to 0.72 to 1.08 MJ per kg of CO_2 plus heat consumption of 5.4 to 7.2 MJ per kg of CO_2.

The CO_2 is subsequently liquefied and stored. The electricity requirement for CO_2 liquefaction amounts to 0.74 MJ per kg of CO_2.

The investment for CO_2 extraction from ambient air after [Breyer et al 2011] comes to 500 €/kW. Again, this estimate refers to the electrical power consumption of the electrolyser producing hydrogen for methanation. Considering the electricity consumption reported in [Breyer et al 2011], the resulting costs amount to 825 €/kW methane.

If the temperature swing adsorption technology developed by Climeworks were used for CO_2 capture from air, the investment would be slightly higher. However, because a part of the heat consumption is supplied by the heat released by the exothermal methanation reaction, the electricity consumption would be lower.

5.1.4.3 Overall process

Table 32 and Table 33 show the techno-economic data for the power-to-gas (PtG) plant using low temperature electrolysis.

Table 32: Techno-economics for $PtCH_4$ via low temperature electrolysis and methanation, CO_2 capture from air via electrodialysis

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	26	24	126	120	120
Capacity	MW_{PtG}	10	10	54	54	54
Efficiency		39%	42%	43%	45%	45%
Investment						
Electrolysis	M€	27	18	39	24	22
H_2 storage	M€	0	0	2	2	2
CO_2 supply	M€	11	11	55	55	55
Methanation	M€	7	7	36	36	36
Total	M€	46	37	132	117	115
	€/kW_{PtG}	4,607	3,678	2,435	2,166	2,131
Overall costs (Germany)						
Costs of EE-CNG	€/GJ	135.5	117.6	84.9	74.7	70.2
Costs of EE-LNG	€/GJ	135.8	117.8	85.2	75.0	70.4

Table 33: Techno-economic data for $PtCH_4$ via low temperature electrolysis and methanation, CO_2 capture from air via temperature swing adsorption (TSA)

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	23	21	112	106	106
Capacity	MW_{PtG}	10	10	54	54	54
Efficiency		43%	47%	48%	51%	51%
Investment						
Electrolysis	M€	27	18	39	24	22
H_2 storage	M€	0	0	2	2	2
CO_2 supply	M€	18	18	69	69	69
Methanation	M€	7	7	36	36	36
Total	M€	53	44	145	131	129
	€/kW_{PtG}	5,290	4,361	2,685	2,416	2,381
Overall costs (Germany						
Costs of EE-CNG	€/GJ	129.4	111.8	79.2	69.6	65.6
Costs of EE-LNG	€/GJ	129.7	112.1	79.5	69.9	65.9

As mentioned above, instead of low temperature electrolysis high temperature electrolysis based on solid oxide electrolysis cells (SOEC) can be used. Table 34 and Table 35 show the techno-economic data for the power-to-gas (PtG) plant using high temperature electrolysis.

Table 34: Techno-economics for $PtCH_4$ via high temperature electrolysis and methanation, CO_2 capture from air via electrodialysis

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	19	19	100	100	100
Capacity	MW_{PtG}	10	10	54	54	54
Efficiency		53%	53%	54%	54%	54%
Investment						
Electrolysis	M€	30	11	32	21	20
H_2 storage	M€	0	0	0	0	0
CO_2 supply	M€	11	11	55	55	55
Methanation	M€	7	7	36	36	36
Total	M€	48	29	123	112	111
	€/kW_{PtG}	4,781	2,900	2,278	2,075	2,044
Overall costs (Germany)						
Costs of EE-CNG	€/GJ	145.5	99.7	70.7	64.6	60.7
Costs of EE-LNG	€/GJ	145.8	100.1	71.0	65.0	61.2

Table 35: Techno-economic data for $PtCH_4$ via high temperature electrolysis and methanation, CO_2 capture from air via temperature swing adsorption (TSA)

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	18	18	93	93	93
Capacity	MW_{PtG}	10	10	54	54	54
Efficiency		57%	57%	58%	58%	58%
Investment						
Electrolysis	M€	30	11	32	21	20
H_2 storage	M€	0	0	0	0	0
CO_2 supply	M€	18	18	69	69	69
Methanation	M€	7	7	36	36	36
Total	M€	55	36	137	126	124
	€/kW_{PtG}	5,464	3,583	2,528	2,326	2,294
Overall costs (Germany						
Costs of EE-CNG	€/GJ	144.6	99.0	73.1	67.3	63.7
Costs of EE-LNG	€/GJ	144.9	99.3	73.5	67.7	64.2

5.1.4.4 Distribution and refueling

The methane produced is transported to refuelling stations via the natural gas grid. The electricity consumption of CNG refuelling stations typically amounts to 0.022 MJ/MJ CNG [JEC 2014] (see chapter 5.1.3). The required electricity is supplied by the electricity grid.

The liquefaction of the methane is carried out onsite the LNG refuelling station to provide LNG. The electricity consumption of the liquefaction plant amounts to about 0.06 kWh per kWh of LNG. Table 36 shows the technical and economic data for CH_4 liquefaction onsite at the refueling station.

Table 36: CH_4 liquefaction

Parameter	Amount
Capacity	8676 kW_{CH4}
Electricity consumption	0.060 $kWh/kWh_{CH4,\ LHV}$
Investment	3.9 million €
Lifetime	20 yr
Operating and maintenance	4% of investment/yr
Equivalent full load period	8300 h/yr

The electricity consumption has been derived from theCH_4 liquefaction plant 'CRYOBOX' with a capacity of 500 kg LNG per hour (6945 kW_{CH4}, LHV) offered by Galileo [Galileo 2013]. The investment has been derived from a natural gas liquefaction plant with a capacity of 2500 kg LNG per hour in Norway via downscaling using a scaling exponent of 0.7. The investment for the Norwegian 2500 kg LNG/hr plant has been indicated with 85 million DKK (10.4 million €) [OED 2013]. The costs for operating and maintenance have been derived from [Bauer & Schmittinger 1996].

The same LNG refueling station as in case of fossil LNG has been used (5.1.3).

5.1.5 Liquid fuels from crude-oil (fossil reference)

For the calculation of the energy requirement and GHG emissions for the supply of gasoline and diesel from crude oil the same assumption as in [JEC 2014] have been applied except the GWP factors (in [JEC 2014] the GWP factors from the IPCC AR4 instead of IPCC AR5 has been used).

Table 37 shows the GHG emissions and the energy use for the supply and use (combustion) of gasoline and diesel from crude oil.

Table 37: GHG emissions and energy use for the supply and use of gasoline and diesel from crude oil

	Gasoline	Kerosene, Diesel
GHG emissions (g CO2 equivalent/MJ)		
WTT	13.9	15.5
TTW	73.3	73.2
Total	87.2	88.7
Energy loss (MJ/MJ)		
WTT	0.18	0.20
TTW	1.00	1.00
Total	1.18	1.20

For gasoline and diesel from crude oil the same GHG emissions and the same energy requirement has been used for all time horizons.

The crude oil price has been derived from the 'World Energy Outlook 2014' ('450 ppm scenario') published by the IEA [IEA 2014]. The gasoline and diesel price has been derived from the crude oil price by multiplication with specific crude oil input of the refinery and adding the costs for refining and distribution which has been derived from [JEC 2007].

Table 38: Crude oil price and resulting price for gasoline and diesel

		2015	2020	2030	2040	2050
Crude oil price	US$/bbl	60	105	102	100	100
	€/bbl	54	79	77	75	75
	€/kWh	0.034	0.050	0.048	0.047	0.047
	€/GJ	9.4	13.8	13.4	13.1	13.1
Gasoline (w/o tax)	€/l	0.41	0.56	0.55	0.54	0.54
	€/kWh	0.046	0.063	0.062	0.061	0.061
	€/GJ	12.8	17.5	17.1	16.8	16.8
Diesel (w/o tax)	€/l	0.47	0.64	0.62	0.61	0.61
	€/kWh	0.047	0.064	0.063	0.061	0.061
	€/GJ	13.0	17.8	17.4	17.1	17.1

The exchange rate for 2015 has been assumed to be 0.8953 €/US$ (average exchange rate in May 2015). For 2020 and later the exchange rate has been assumed to be 0.75 €/US$.

5.1.6 PtL (gasoline, jet fuel, diesel) from renewable electricity

5.1.6.1 Hydrogen generation

Hydrogen is generated via water electrolysis (see chapter 5.1.2.1). For pathways involving power-to-methane and power-to-liquid the specific data for the larger electrolysis plants (5 MW_e and 100 MW_e) has been used. Further, a variant using solid oxide electrolysis cells (SOEC) has been considered.

As well as the methanol synthesis and the Fischer-Tropsch synthesis is exothermal. If high temperature electrolysis with solid oxide electrolysis cells (SOEC) is used the heat released by the synthesis step (220-250°C) can be used to generate steam for the electrolysis. The electrolysis of steam requires less electricity than the electrolysis of liquid water. The German company Sunfire has developed such a process which achieves an efficiency of almost 70% without CO_2 supply for the combined electrolysis and Fischer-Tropsch syntheses process based on the LHV. In case of low temperature electrolysis only about 50% can be achieved without taking into account the energy requirement for CO_2 supply.

5.1.6.2 Synthesis and further processing

In case of the ‘methanol route’ at first the hydrogen is converted to methanol:

$$3\,H_2 + CO_2 \rightarrow CH_3OH_{liquid} + H_2O_{liquid} \qquad \Delta H_{298K} = -130.97\ kJ$$

$$(3\,H_2 + CO_2 \rightarrow CH_3OH_g + H_2O_g \qquad \Delta H_{298K} = -49.57\ kJ)$$

The reaction is exothermal. It has been assumed that the CO_2 is extracted from ambient air.

Subsequently the methanol is converted to synthetic gasoline, kerosene, and diesel via olefin syntheses (with DME synthesis as intermediate step), oligomerisation, and hydrotreating:

DME synthesis: $2\,CH_3OH \rightarrow CH_3\text{-}O\text{-}CH_3 + H_2O$

Olefin synthesis: $CH_3\text{-}O\text{-}CH_3 \rightarrow (CH_2)_2 + 2\,H_2O$

Oligomerisation: $0.5\,n\,(CH_2)_2 \rightarrow C_nH_{2n}$

Hydrotreating: $C_nH_{2n} + H_2 \rightarrow C_nH_{2n+2}$

At maximum diesel mode the liquid product consists of 81% (mass) diesel and kerosene, 10% (mass) gasoline, and 9% (mass) LPG [Liebner et al 2004]. At maximum gasoline mode the product consists of 88% (mass) gasoline and 12% (mass) LPG. The octane number (RON) is indicated with 97 [Schulien 1995]. As a result the shard of diesel, kerosene and diesel can be varied in a wide range. In this study it has been assumed that the LPG fraction is used for electricity and heat generation.

In case of the 'Fischer-Tropsch-Route' the hydrogen is converted to hydrocarbons via Fischer-Tropsch synthesis:

$$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$

The reaction is exothermal. The CO is produced from CO_2 via inverse CO shift. It has been assumed that the CO_2 is extracted from ambient air.

In order to get maximum yields of liquid hydrocarbons and minimum yields of gases, the FT synthesis is carried out in such a way that predominantly heavy products (heavy paraffin) are generated. In a following process step the heavy paraffins are cracked into lighter hydrocarbons via hydrocracking.

This approach is applied e.g. in case of the Shell Middle Distillate Syntheses (SMDS). At maximum diesel mode the liquid product consists of 60% gasoil, 25% kerosene and 15% naphtha [Senden 1996], [Senden 1998].

5.1.6.3 Overall process

Figure 29 shows a simplified process flow diagram for production of gasoline, kerosene, and diesel via the methanol route combined with low temperature water electrolysis.

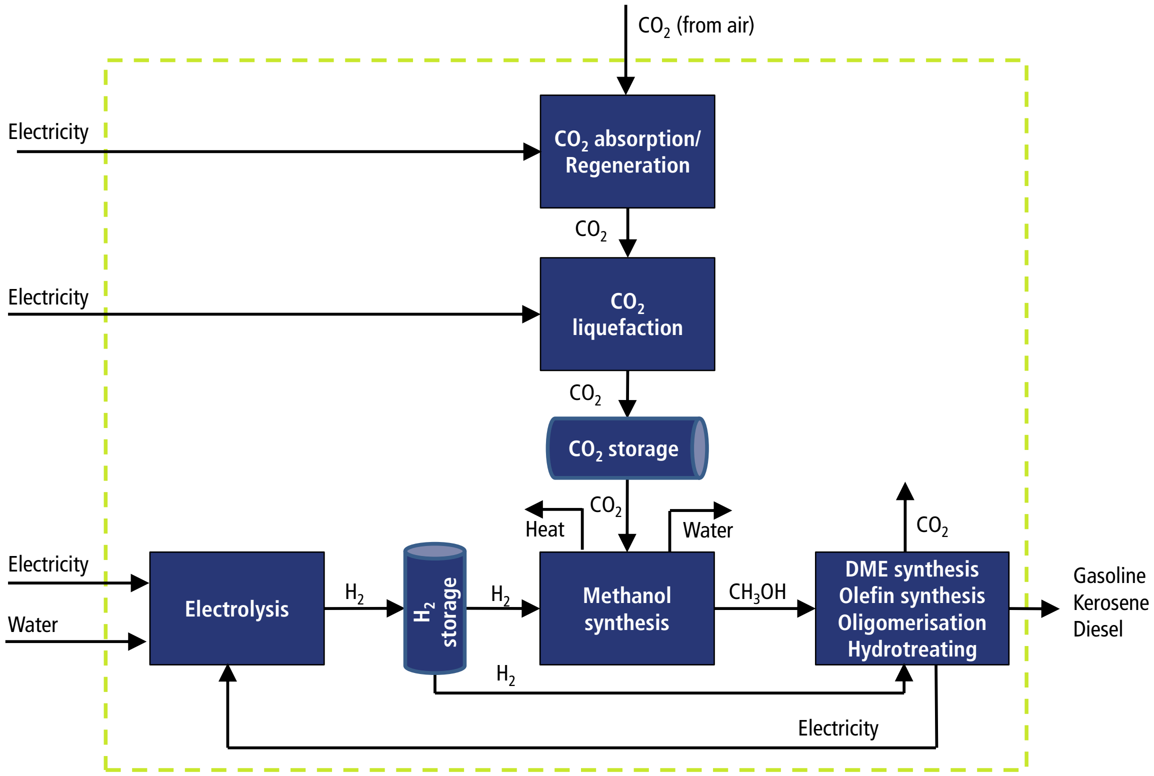


Figure 29: **PtL via the methanol route combined with low temperature water electrolysis**

Table 39 shows the technical and economic data for production of gasoline, kerosene, and diesel via the methanol route combined with low temperature water electrolysis.

Table 39: Technical and economic data for PtL via the methanol route combined with low temperature electrolysis, CO_2 captured from air via electrodialysis

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	27	25	133	127	127
Capacity	MW_{PtG}	9	9	50	50	50
Efficiency		34%	37%	38%	40%	40%
Investment						
Electrolysis	M€	27	18	39	24	22
H_2 storage	M€	1	1	3	3	3
CO_2 supply	M€	14	14	70	70	70
Synthesis, methanol conversion	M€	8	8	28	28	28
Total	M€	51	42	139	125	123
	€/kW_{PtG}	5,458	4,460	2,760	2,472	2,434
Overall costs (Germany)						
Fuel costs WTT	€/GJ_{PtL}	147	127	90	79	74
	€/MWh_{PtL}	528	459	323	283	265
Thereof CO_2 costs	€/MWh_{PtL}	128	124	96	90	86
	€/t_{CO2}	463	450	349	327	310

If high temperature steam electrolysis is applied the heat from the exothermal methanol synthesis reaction is used for steam generation. Furthermore, the gaseous fraction from the conversion of methanol to gasoline, kerosene, and diesel is used for steam production instead for electricity generation. Figure 30 shows a simplified process flow diagram for production of gasoline, kerosene, and diesel via the methanol route combined with high temperature steam electrolysis based on solid oxide electrolysis cells (SOEC).

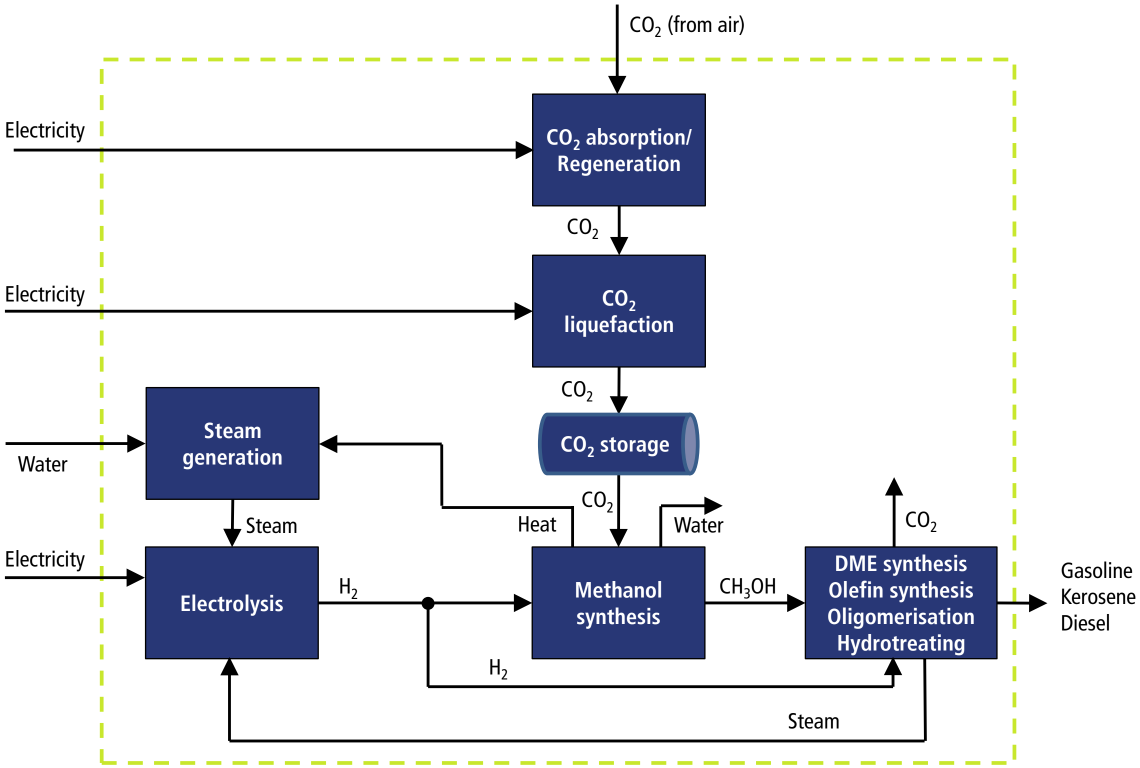


Figure 30: **PtL via the methanol route combined with high temperature steam electrolysis based on SOEC**

The electrolysis is directly connected with the methanol synthesis. Therefore, no hydrogen storage is installed between electrolysis and methanol synthesis. This leads to the disadvantage of lower capability to follow the electricity supply from renewable electricity sources. Probably electricity storage e.g. Redox-Flow batteries are required if the plant is located nearby a wind farm or a large photovoltaic (PV) power station. Another solution could be to install the PtL plant nearby a concentrating thermal solar power station with thermal electricity storage at location with high direct solar insolation e.g. in Southern Spain or Morocco.

Table 40 shows the technical and economic data for production of gasoline, kerosene, and diesel via the methanol route combined with high temperature steam electrolysis.

Table 40: Technical and economic data for PtL via the methanol route combined with high temperature electrolysis, CO_2 captured from air via electrodialysis

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW$_e$	29	29	144	144	144
Capacity	MW$_{PtG}$	13	13	65	65	65
Efficiency		44%	44%	45%	45%	45%
Investment						
Electrolysis	M€	41	15	42	28	25
H_2 storage	M€	0	0	0	0	0
CO_2 supply	M€	20	20	90	90	90
Synthesis, methanol conversion	M€	11	11	33	33	33
Total	M€	72	45	164	150	148
	€/kW$_{PtG}$	5,511	3,491	2,524	2,307	2,274
Overall costs (Germany)						
Fuel costs WTT	€/GJ$_{PtL}$	163	114	79	72	67
	€/MWh$_{PtL}$	585	411	283	258	242
Thereof CO_2 costs	€/MWh$_{PtL}$	127	123	96	90	85
	€/t$_{CO2}$	460	447	348	326	309

Lower lifetime of SOEC leads to higher overall costs for the supply of gasoline, kerosene, and diesel in 2015.

Figure 31 shows a simplified process flow diagram for production of gasoline, kerosene, and diesel via the Fischer-Tropsch route combined with low temperature water electrolysis.

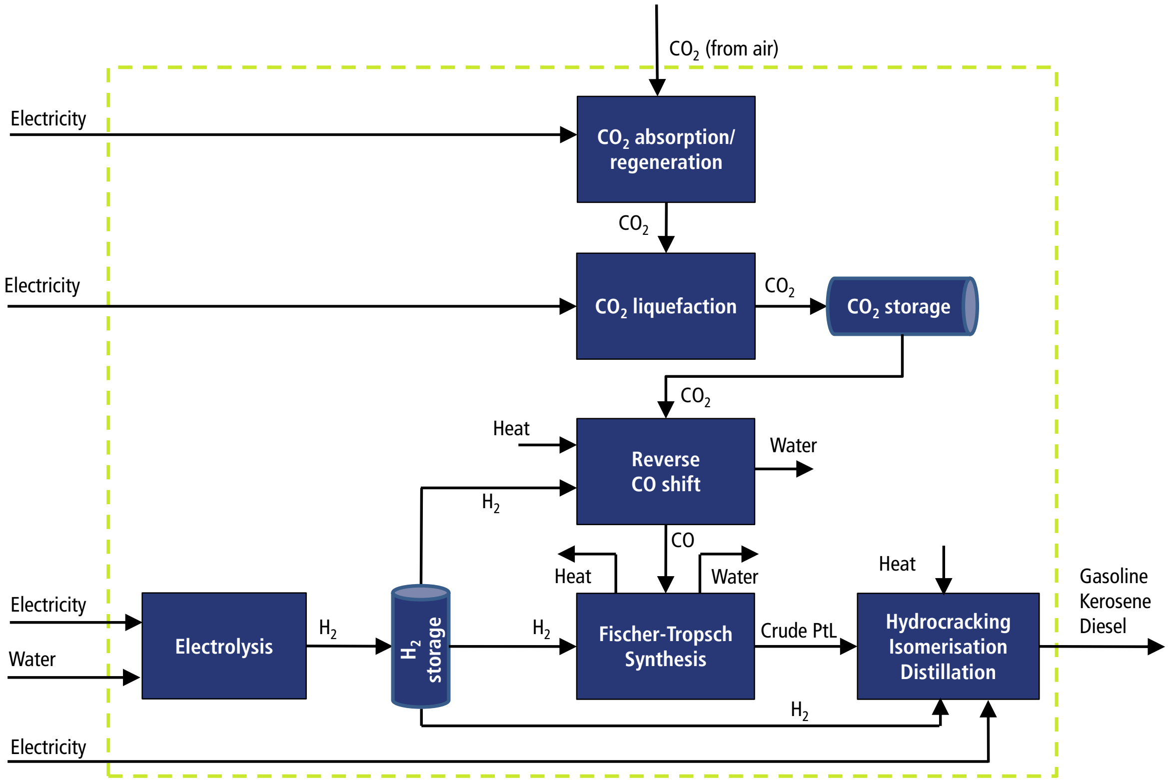


Figure 31: **PtL via the Fischer-Tropsch route combined with low temperature water electrolysis**

In case of Fischer-Tropsch synthesis larger hydrogen storage capacity is required than for the methanol synthesis (50 h of full load operation instead of 3 h) due to lower ramp up time.

Table 41 shows the technical and economic data for production of gasoline, kerosene, and diesel via the Fischer-Tropsch route combined with low temperature water electrolysis.

Table 41: **Technical and economic data for PtL via the Fischer-Tropsch route combined with low temperature electrolysis, CO_2 captured from air via electrodialysis**

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	27	25	132	126	126
Capacity	MW_{PtG}	9	9	49	49	49
Efficiency		34%	37%	37%	39%	39%
Investment						
Electrolysis	M€	27	18	39	24	22
H_2 storage	M€	6	6	30	30	30
CO_2 supply	M€	14	14	70	70	70
Synthesis, Upgrading	M€	8	8	26	26	26
Total	M€	55	46	165	151	149
	€/kW_{PtG}	6,130	5,101	3,373	3,075	3,036
Overall costs (Germany)						
Fuel costs WTT	€/GJ_{PtL}	153	133	95	83	78
	€/MWh_{PtL}	550	479	340	299	281
Thereof CO_2 costs	€/MWh_{PtL}	131	128	99	93	88
	€/t_{CO2}	463	450	349	327	310

Figure 32 shows a simplified process flow diagram for production of gasoline, kerosene, and diesel via the Fischer-Tropsch route combined with high temperature steam electrolysis based on solid oxide electrolysis cells (SOEC).

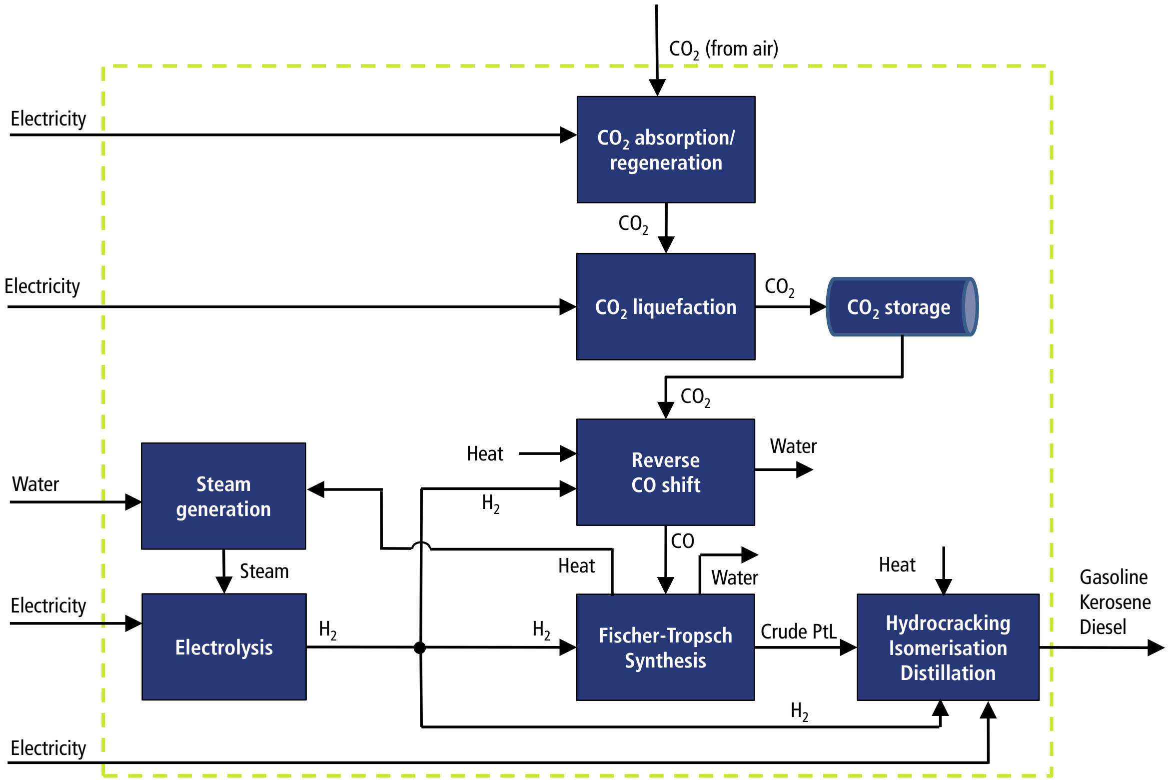


Figure 32: PtL via the Fischer-Tropsch route combined with high temperature steam electrolysis based on SOEC

Table 42 shows the technical and economic data for production of gasoline, kerosene, and diesel via the Fischer-Tropsch route combined with high temperature steam electrolysis.

Table 42: Technical and economic data for PtL via the Fisher-Tropsch route combined with high temperature electrolysis, CO_2 captured from air via electrodialysis

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	28	28	139	139	139
Capacity	MW_{PtG}	13	13	63	63	63
Efficiency		44%	44%	45%	45%	45%
Investment						
Electrolysis	M€	41	15	42	28	25
H_2 storage	M€	0	0	0	0	0
CO_2 supply	M€	20	20	89	89	89
Synthesis, Upgrading	M€	10	10	31	31	31
Total	M€	71	45	162	148	146
	€/kW$_{PtG}$	5,626	3,543	2,567	2,344	2,309
Overall costs (Germany)						
Fuel costs WTT	€/GJ$_{PtL}$	164	114	79	72	67
	€/MWh$_{PtL}$	590	411	283	258	242
Thereof CO_2 costs	€/MWh$_{PtL}$	131	127	99	93	88
	€/t$_{CO2}$	460	447	348	326	309

Table 43 shows the technical and economic data for production of gasoline, kerosene, and diesel via the Fischer-Tropsch route combined with high temperature steam electrolysis if the CO_2 is captured from air via temperature swing adsorption (TSA). This technology is proposed by Sunfire.

Table 43: **Technical and economic data for PtL via the Fisher-Tropsch route combined with high temperature electrolysis, CO_2 captured from air via TSA**

	Unit	2015	2020	2030	2040	2050
Technical key data						
Electricity input	MW_e	27	27	134	134	134
Capacity	MW_{PtG}	13	13	63	63	63
Efficiency		46%	46%	47%	47%	47%
Investment						
Electrolysis	M€	41	15	42	28	25
H_2 storage	M€	0	0	0	0	0
CO_2 supply	M€	29	29	103	103	103
Synthesis, Upgrading	M€	10	10	31	31	31
Total	M€	80	54	175	161	159
	€/kW_{PtG}	6,363	4,281	2,776	2,552	2,517
Overall costs (Germany)						
Fuel costs WTT	€/GJ_{PtL}	165	115	78	71	67
	€/MWh_{PtL}	595	416	280	255	240
Thereof CO_2 costs	€/MWh_{PtL}	135	132	95	90	86
	€/t_{CO2}	476	464	336	316	301

The overall costs of transportation fuel are approximately the same as for the variant where CO_2 absorption via scrubbing with NaOH, stripping with H_2SO_4 and regeneration via electrodialysis is applied.

5.1.6.4 Distribution of final fuel

For the distribution of the final fuel the same assumptions as in [JEC 2014] has been made. The final fuel is transported to a depot via a 40 t truck over a distance of 150 km (one way). From there, the final fuel is transported to the refueling stations via a 40 t truck over a distance of 150 km. The electricity requirement of the refueling station amounts to 0.0034 MJ per MJ of final fuel is met by electricity from the electricity mix (0.4 kV level).

5.1.7 CO_2 supply

For the methanation and for the synthesis of liquid hydrocarbons CO_2 is required which can either be sourced from concentrated sources or extracted from the air.

One option to extract CO_2 from the air is via scrubbing using a scrubbing agent, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), which is converted to sodium carbonate (Na_2CO_3) or potassium carbonate (K_2CO_3), respectively. The decomposition is done via electrodialysis.

The ZSW process described in [Specht et al 1996] is based on absorption with sodium hydroxide (NaOH), stripping the CO_2 with sulphuric acid (H_2SO_4), and regeneration of the Na_2SO_4 via electrodialysis. The following reactions occur:

CO_2 absorption: $CO_2 + 2\ NaOH \rightarrow Na_2CO_3 + H_2O$

Stripping: $Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + CO_2 + H_2O$

Electrodialysis: $Na_2SO_4 + H_2O \rightarrow 2\ NaOH + H_2SO_4$

The specific electricity consumption depends on the current density of the elecrodialysis plant. The higher the current density the higher is the specific electricity consumption. At a current density of 100 mA per cm^2 of electrodialysis cell area the electricity consumption for the whole process including fan blower amounts to 430 kJ per mole of CO_2 or about 9.8 MJ per kg of CO_2 [Specht et al 1998]. [Specht 1999] indicates an electricity consumption of about 12.3 MJ per kg of CO_2 due to a higher current density.

[Sterner 2009] indicates an energy consumption of about 8.2 MJ per kg of CO_2 for the extraction of CO_2 from air via the ZSW process (thereof 6.4 MJ/kg for the electrodialysis for regeneration of the scrubbing agent).

In [Eisaman et al 2010] a process has been described where KOH is used as scrubbing agent. The following reactions occur:

CO_2 absorption: $2\ KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

$CO_2 + KOH \rightarrow KHCO_3$

Electrodialysis: $K_2CO3 + H_2O \rightarrow CO_2 + 2\ KOH$

$KHCO_3 \rightarrow CO_2 + KOH$

The electricity consumption is indicated with 300 kJ per mole of CO_2 (thereof 100 kJ for the electrodialysis of the $KHCO_3$ solution from CO_2 absorption with KOH) which leads to about 6.8 MJ per kg of CO_2.

The process which has been developed by the Canadian company Carbon Engineering (CE) consists of CO_2 absorption with KOH, formation of $CaCO_3$ from K_2CO_3 and regeneration of the $CaCO_3$ via calcination and subsequently conversion to $Ca(OH)_2$. The following reactions occur:

CO_2 absorption: $2\ KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

Regeneration of KOH: $K_2CO_3 + Ca(OH)_2 \rightarrow 2\ KOH + CaCO_3$

Calcination: $CaCO_3 \rightarrow CaO + CO_2$

Regeneration of $Ca(OH)_2$ $CaO + H_2O \rightarrow Ca(OH)_2$

The calcination process requires very high temperatures of more than 800°C to convert the $CaCO_3$ back to CaO to recover the CO_2. Carbon Engineering assumes that natural gas is used as fuel for the calcination process and for the supply of electricity for the whole process and indicates a natural gas consumption of about 10 MJ per kg of CO_2 [CE 2015]. The theoretical minimum heat requirement for the calcination reaction amounts to about 4.1 MJ per kg of CO_2.

A demo plant is currently under construction. Carbon Engineering plans to build a first-of-a-kind commercial air capture plant in 2017.

The Swiss company Climeworks (a spinoff of the ETH Zurich) uses an adsorption/desorption cycle to extract CO_2 from the air. The CO_2 is chemically bound on a sorbent (in contrast to most adsorption processes chemisorption instead of physisorption is applied here). The regeneration of the sorbent is carried out by low temperature heat (95°C). The process can also be referred to as a temperature swing adsorption (TSA) process.

Table 44 shows a comparison of various technologies for the extraction of CO_2 from air.

Table 44: **CO_2 extraction from air**

	Unit	ZSW	PARC	CE	Climeworks	This study
Technology		Absorption/ Electrodialysis	Absorption/ Electrodialysis	Absorption/ Calcination	Adsorption/ Desorption	Absorption/ Electrodialysis
Natural gas	MJ/kg_{CO2}	-	-	10*	-	-
Heat	MJ/kg_{CO2}	-	-	-	5.4-7.2	-
Electricity	MJ/kg_{CO2}	8.2-12.3	6.8	-	0.72-1.08	8.2
T (heat)	°C	n. a.	n. a.	>850°C	95%	n. a.
CO_2 purity		>99%	>99%	-	>99.5%	-

* Natural gas is used for heat and electricity supply;

If there is no high temperature heat source (required for regeneration via calcination), electrodialysis and the system from Climeworks (temperature swing adsorption) will be the adequate technology.

The investment for CO_2 extraction from ambient air via absorption and electrodialysis is indicated with 500 € of kW of electricity input of the electrolyser [Breyer et al 2011]. [Breyer et al 2011] assumes an electrolysis electricity consumption of 1.65 kWh in reference to the lower heating value of methane. As a result the investment for CO2 capture from air amounts to 825 €/kW methane. About 0.198 kg of CO_2 are required per kWh of methane leading to an investment of 4167 €/(kg CO_2/h). Costs for maintenance and repair are reported to amount to 2% of the investment.

Another technology used for the cost calculation is the CO_2 capture from air via temperature swing adsorption (TSA). Table 45 shows the economic data for CO_2 capture from air via TSA for different plant capacities. The economic data supplied by the Swiss company Climeworks from 2015 are indicated in Swiss Franc (CHF) which has been converted to € using an exchange rate of 0.95 €/CHF.

Table 45: Economic data for the CO_2 capture from air via TSA

		0.125 t CO_2/h	2 t CO_2/h	20 t CO_2/h
Investment	€	1,662,500	15,200.000	91,200.000
	€/(kg/h)	13,300	7,600	4,560

From the data in Table 45 a curve for the specific investment depending on the capacity of the plant can be made (Figure 33).

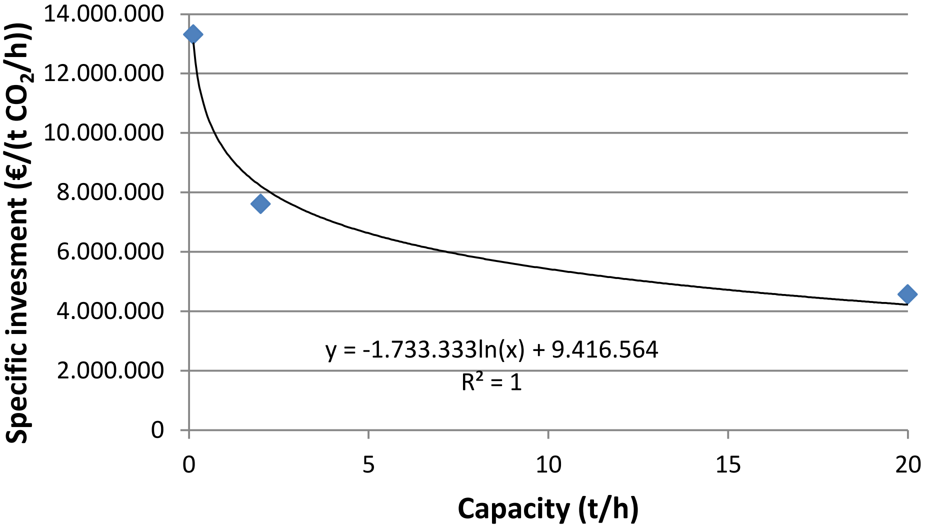


Figure 33: Specific investment for CO_2 capture from air via TSA

From this curve the investment for the CO_2 capture from air via TSA has been calculated.

Pure CO_2 is required with very low O_2 content to avoid damage of the catalysts used for methanation and syntheses. The CO_2 is purified via liquefaction.

The calculation is based on an existing CO_2 liquefaction plant including CO_2 storage onsite an ethanol plant in Lüdinghausen in North Rhine-Westphalia (NRW) in Germany which is in operation since 2013. The temperature of liquefied CO_2 amounts to about -25°C at an elevated pressure and the purity amounts to 99.999% (vol.) [WIR 2014]. The oxygen content after liquefaction is less than 5 ppm [Buchhauser et al 2005] which is sufficient for the catalysts used for methanation and synthesis.

Table 46 shows the technical and economic data for the CO_2 liquefaction plant in Lüdinghausen.

Table 46: CO_2 liquefaction plant incl. storage in Lüdinghausen (NRW)

Parameter	Value
Capacity	2,300 kg CO_2/h
Production	17,000 t CO_2/a
Electricity consumption	3.5 GWh/a
Storage capacity	300 t (3 tanks, each 100 t)
Investment	3.5 million €

The investment for the CO_2 liquefaction plant for the $PtCH_4$ and PtL plants has been derived from the data in Table 46 by scaling to the required capacity using a scaling exponent of 0.7. The maintenance costs have been assumed to be 2% of investment per year.

5.1.8 Electricity for battery-electric vehicles (BEV) and electric trains

Is has been assumed that the electricity for battery-electric vehicles and for electric trains is derived from the electricity mix.

For **battery-electric vehicles (BEV)** only slow-fill charging has been assumed. Neither public fast-fill chargers (such as Tesla's 'super charger') nor 'own consumption' (such as from household rooftop PV) is considered here. For both, the electrical integration into a system with high shares of renewable power would require dedicated comprehensive modelling beyond the scope of this study. The vehicle batteries are recharged at home (electricity at 0.4 kV or 230 V level). Components such as 'wall boxes' are assumed to be a part of the vehicle costs. The battery charger is onboard the vehicle. Therefore, no stationary storage and no additional infrastructure are required for BEV.

Table 47: Renewable electricity costs for BEV charging in Germany (excl. electricity tax, excl. VAT)

DE	2015	2030	2050
Renewable electricity production (incl. losses)	0.103 €/kWh	0.089 €/kWh	0.073 €/kWh
Electricity transport and distribution (incl. concession levy)	0.14 €/kWh	0.14 €/kWh	0.14 €/kWh
Total	**0.243 €/kWh**	**0.229 €/kWh**	**0.212 €/kWh**

Table 48: Renewable electricity costs for BEV charging in EU-28 (excl. electricity tax, excl. VAT)

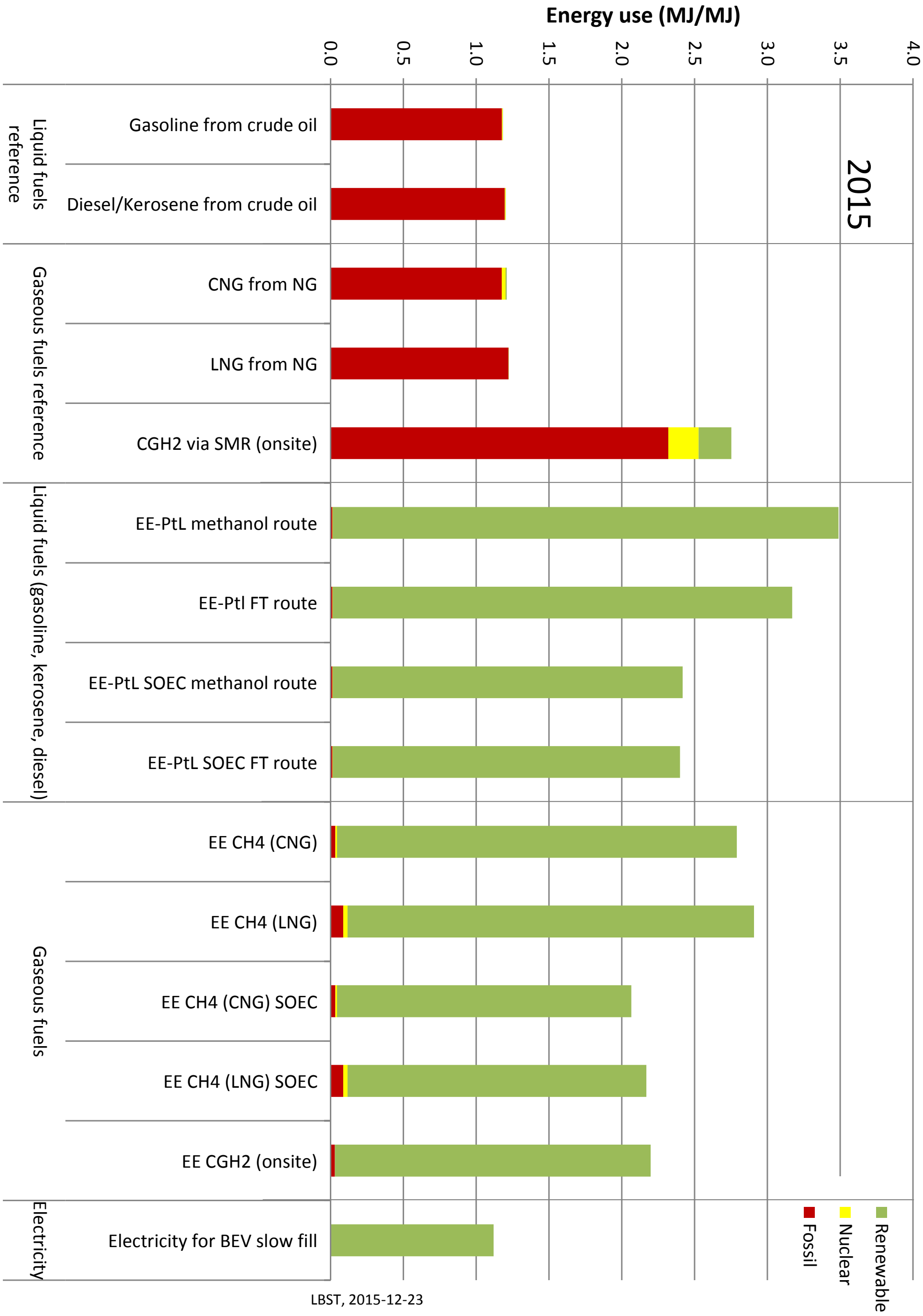
EU	2015	2030	2050
Renewable electricity production (incl. losses)	0.098 €/kWh	0.085 €/kWh	0.070 €/kWh
Electricity transport and distribution (incl. concession levy)	0.14 €/kWh	0.14 €/kWh	0.14 €/kWh
Total	**0.238 €/kWh**	**0.225 €/kWh**	**0.210 €/kWh**

By 2050, electricity for **electric trains** is assumed to be from 100% renewable sources, too. The (fluctuating) renewable power supply has to be matched with the demand profile of electric trains supplied via overhead lines (OHL). For this, it is assumed that 50% of the electricity consumed in electric trains is provided via stationary electricity storage with a roundtrip efficiency of 75% power-to-power, in line with assumptions made in [LBST et al. 2016] and [IFEU/INFRAS/LBST 2015]. This leads to an increase of the specific electricity consumption of electric trains.

5.2 Results fuel supply

5.2.1 Energy use

Figure 34 and Figure 35 shows the primary energy use for different transportation fuels split into fossil, nuclear, and renewable energy for 2015 and 2050 respectively. The energy content of the final fuel is included (embedded energy). The reciprocal value is the efficiency of fuel supply.



LBST, 2015-12-23

Figure 34: **Primary energy use for different transportation fuels in 2015**

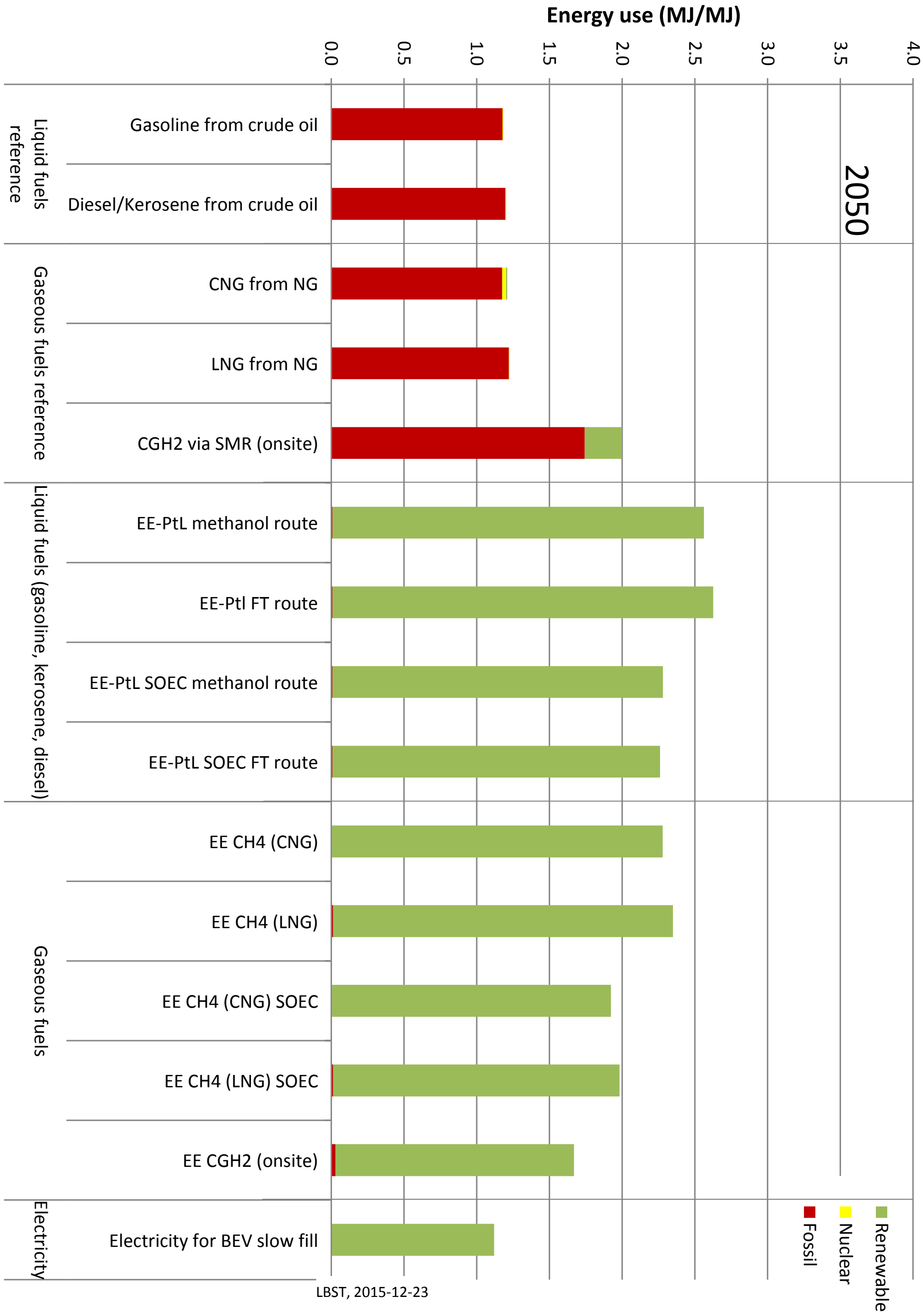


Figure 35: **Energy use for different transportation fuels in 2050**

Renewable transportation fuels show a higher primary energy than fossil transportation fuels. However, the use of fossil and nuclear energy sources and the associated environmental impact (e.g. greenhouse gas emissions and emissions of air pollutants) is almost zero in case of renewable electricity based fuels.

5.2.2 Greenhouse gas emissions

Figure 36 and Figure 37 show the greenhouse gas emissions from the supply and use (combustion e.g. in a vehicle) of different transportation fuels.

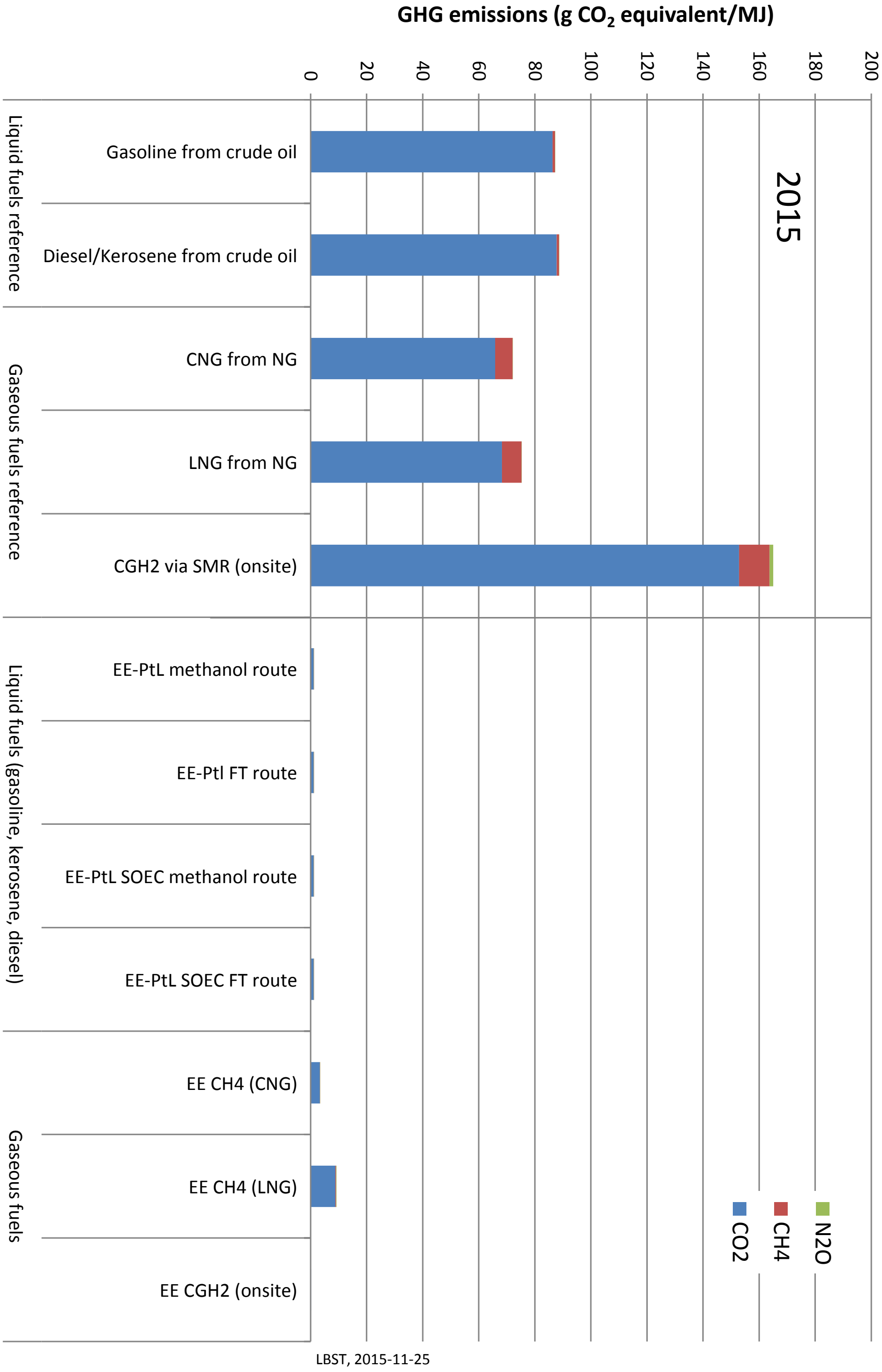
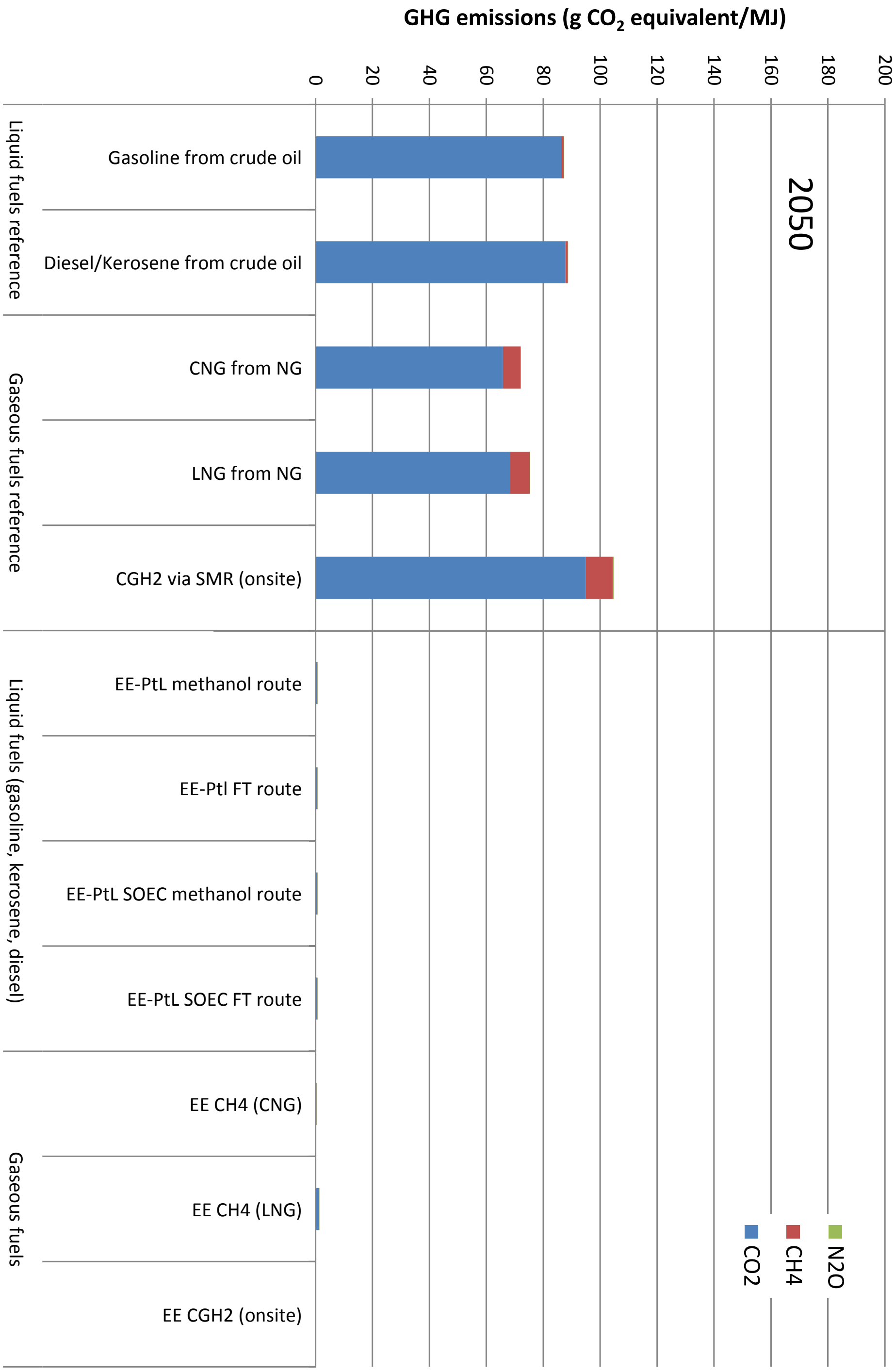


Figure 36: **GHG emissions from the supply and use (combustion) of different transportation fuels in 2015**



LBST, 2015-11-25

Figure 37: GHG emissions from the supply and use (combustion) of different transportation fuels in 2050

Renewable transportation fuels show very low emissions of greenhouse gases (GHG). Small amounts of GHG emissions occur during the transport and distribution of the final fuel via fossil fuel fuelled trucks. In case of CNG LNG small amounts of GHG occur from the use of grid electricity for CH_4 compression and CH_4 liquefaction at the refueling station which decrease towards zero in 2050.

For CGH_2 from natural gas steam reforming the decrease of electricity consumption of the refueling station (lower electricity demand for pre-cooling) and increasing share of renewable electricity in the electricity mix leads to decreasing GHG emissions from auxiliary electricity.

The GHG emissions for the supply of renewable electricity for charging of battery electric vehicles (not shown in the chart) are zero.

5.2.3 Specific fuel and greenhouse gas avoidance costs

Based on the assumptions as laid out in chapter 5.1 the following specific fuel costs and greenhouse gas avoidance costs 'well-to-tank' result for Germany and EU-28 respectively. The significant variable between Germany and EU-28 results hereto are the renewable power mixes and annual electricity yields. For PtX production technologies and fuel distribution technologies, a European market has been assumed, i.e. the same technology learning curves have been applied.

In order for PtL (excluding energy tax and VAT) to achieve today's diesel price of 1.10 ct/$l_{Diesel\text{-}equiv}$ (including energy tax and VAT), renewable electricity prices in the order of 5 ct/kWh_e, high temperature electrolysis, CO_2 from a concentrated source, and 4000 equivalent full load hours per year are required.

a) Germany

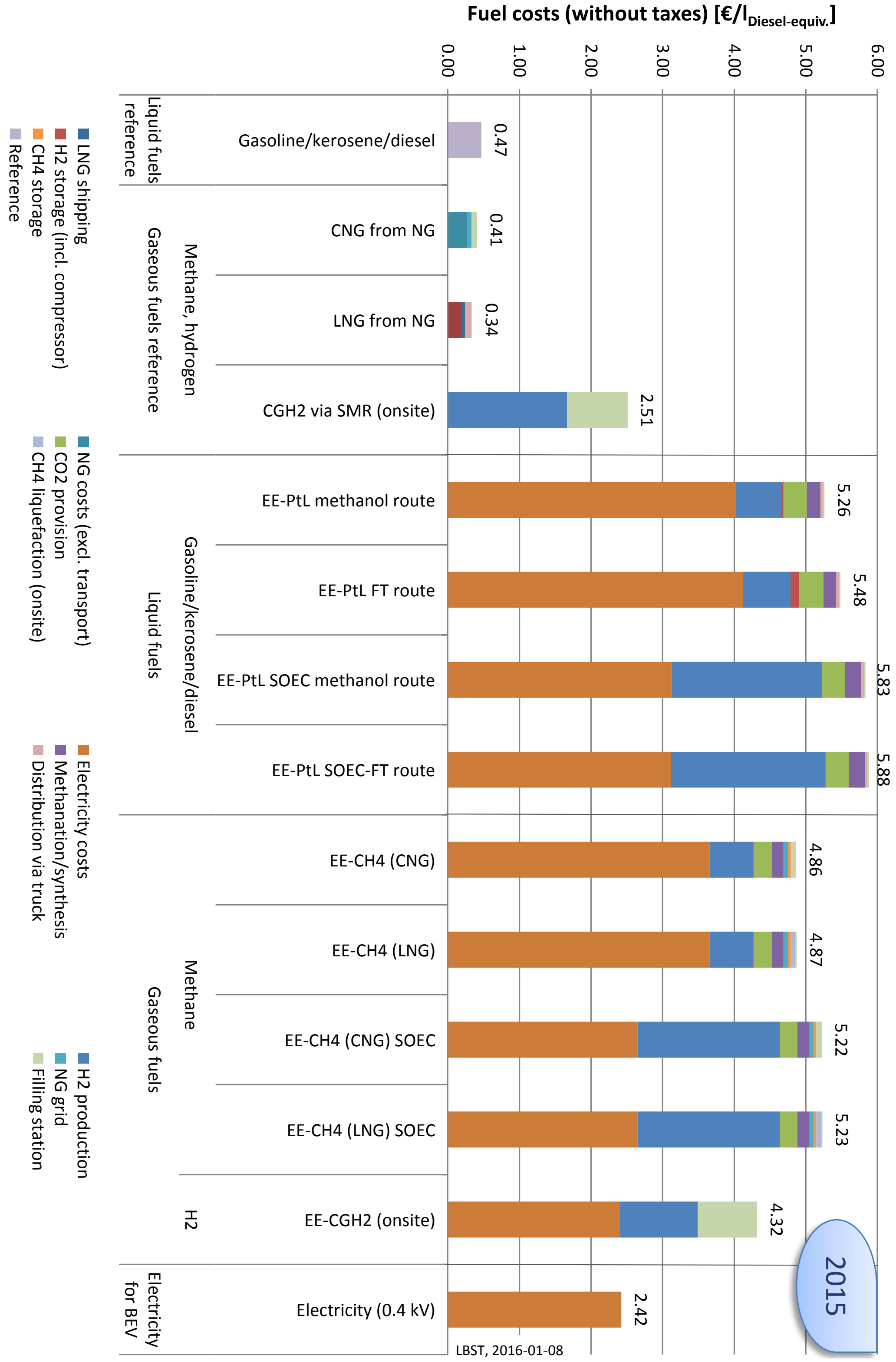


Figure 38: Specific fuel costs (domestic PtX production), 2015, Germany

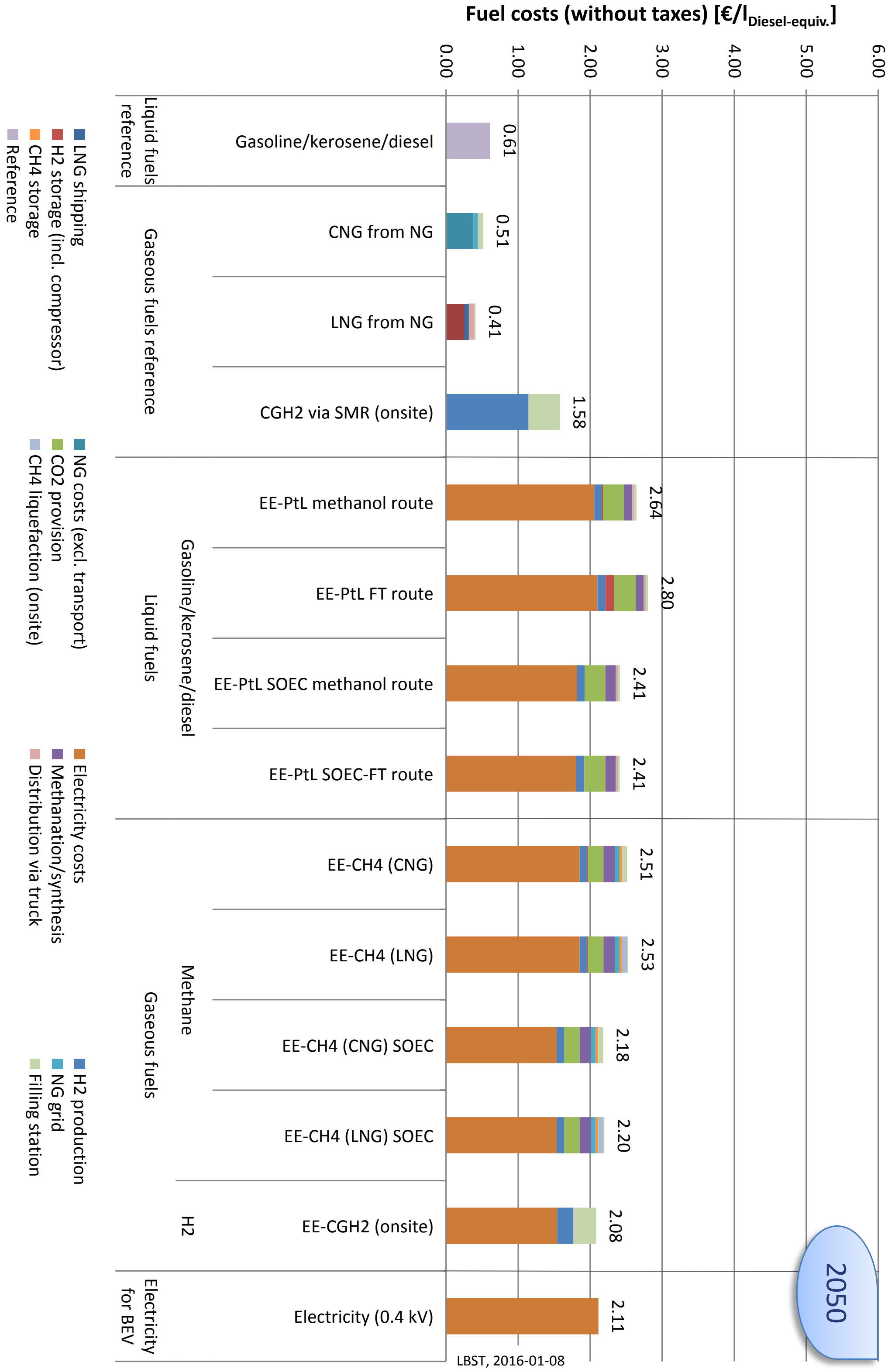


Figure 39: Specific fuel costs (domestic PtX production), 2050, Germany

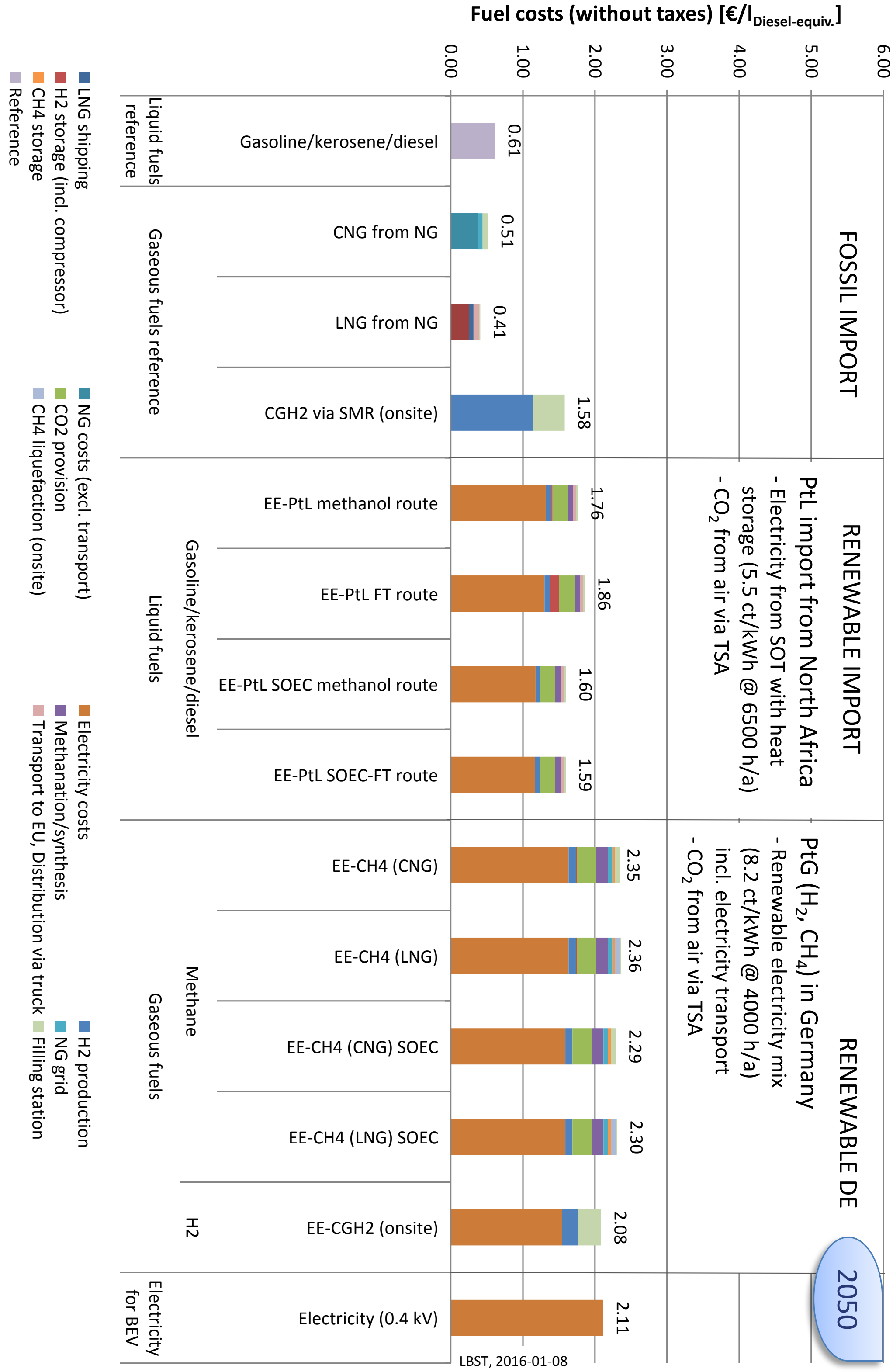
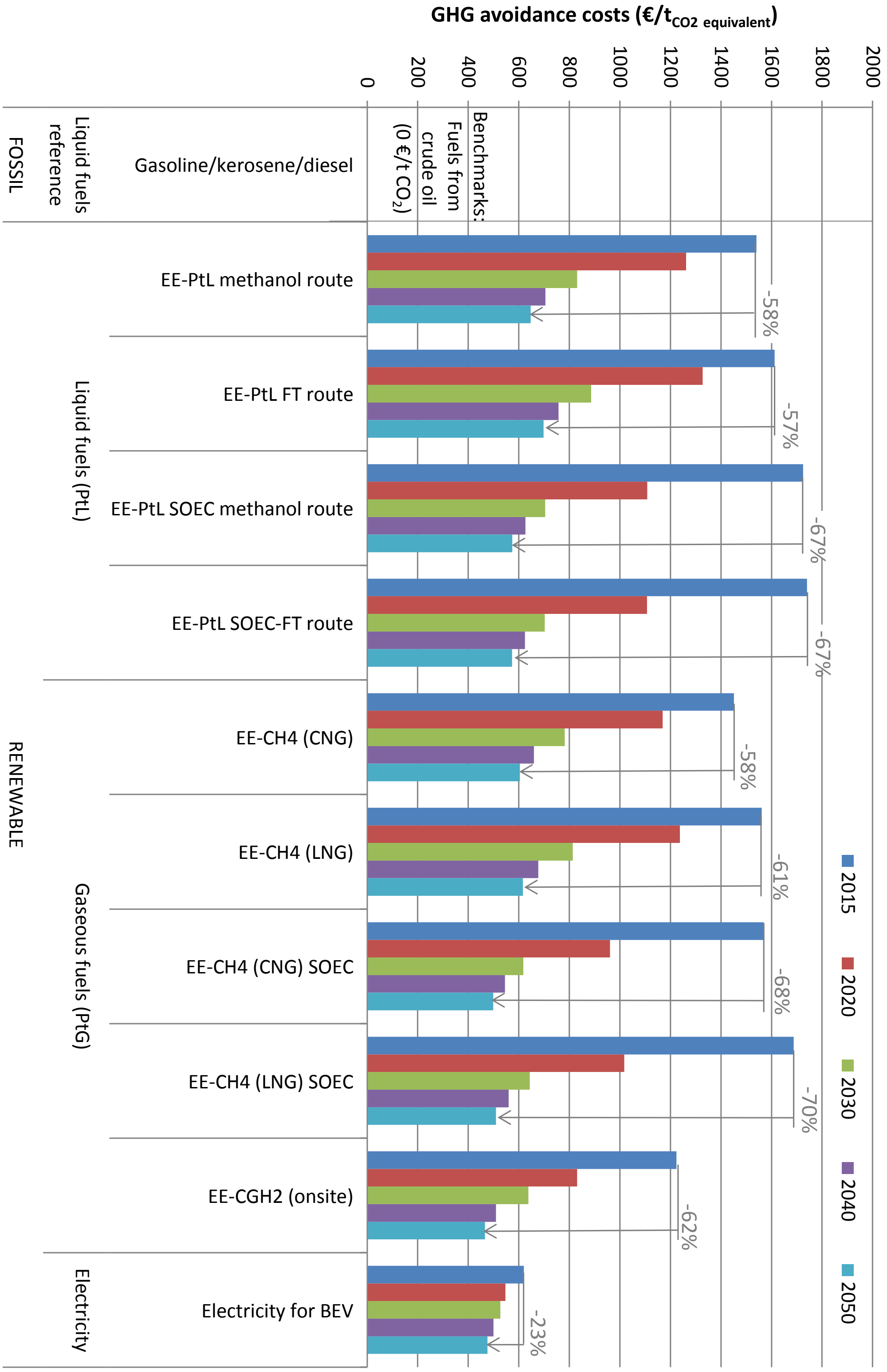


Figure 40: Specific fuel costs (including PtL imports), 2050, Germany



LBST, 2016-01-08

Figure 41: GHG avoidance costs (€/t$_{CO2\text{-}equivalent}$), PtX fuels, Germany

b) Europe

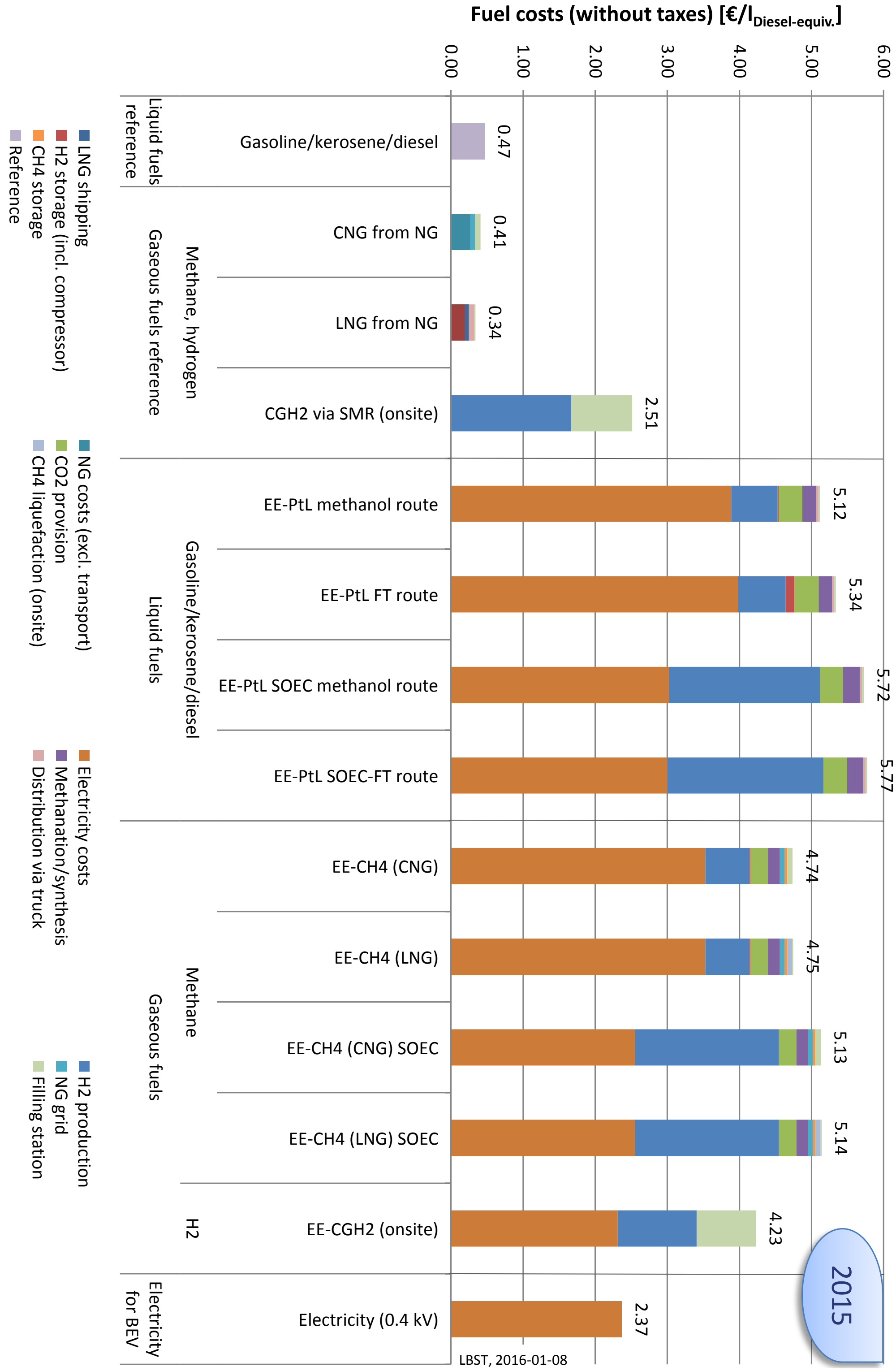


Figure 42: Specific fuel costs (domestic PtX production), 2015, EU

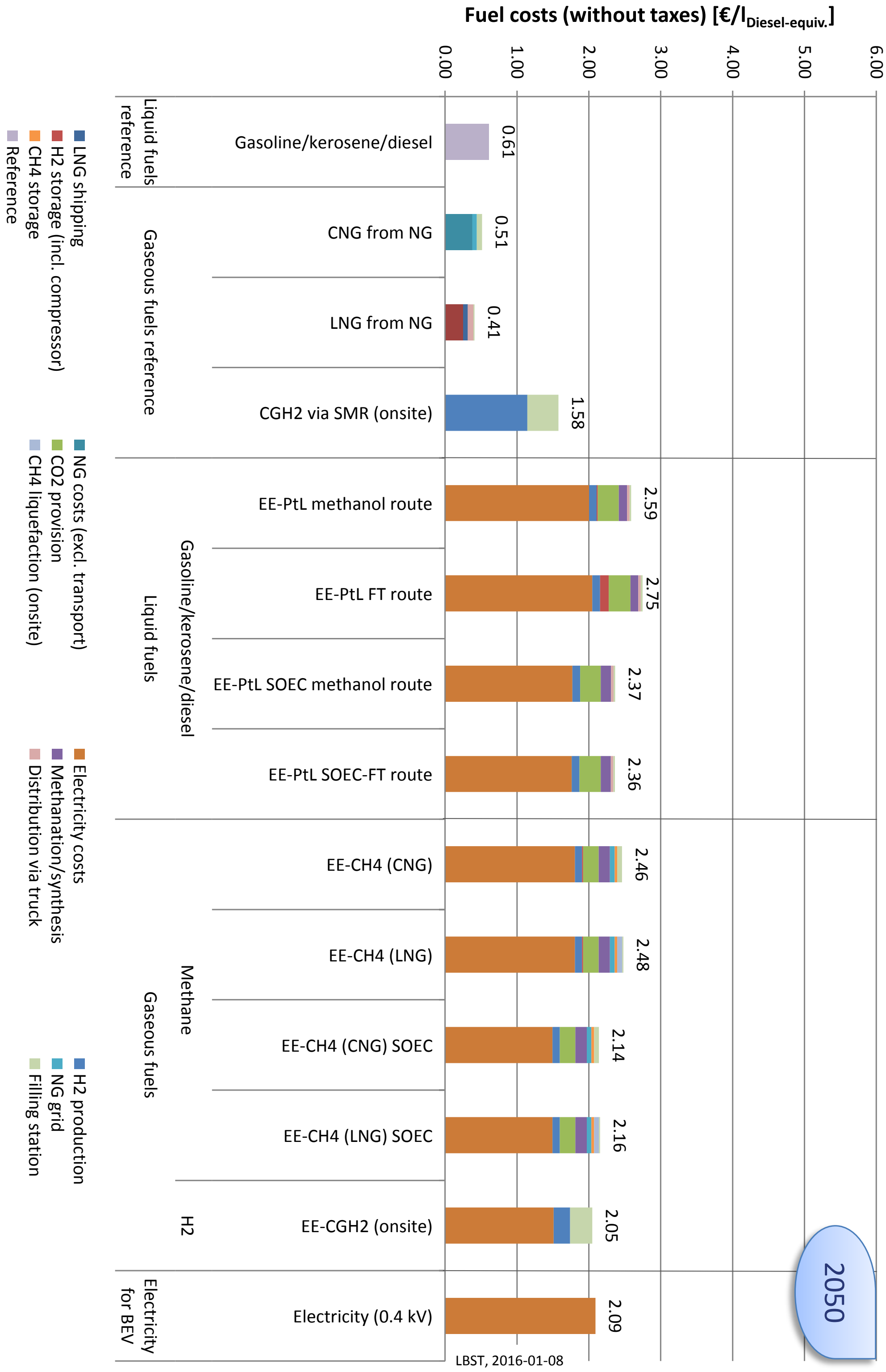


Figure 43: **Specific fuel costs (domestic PtX production), 2050, EU**

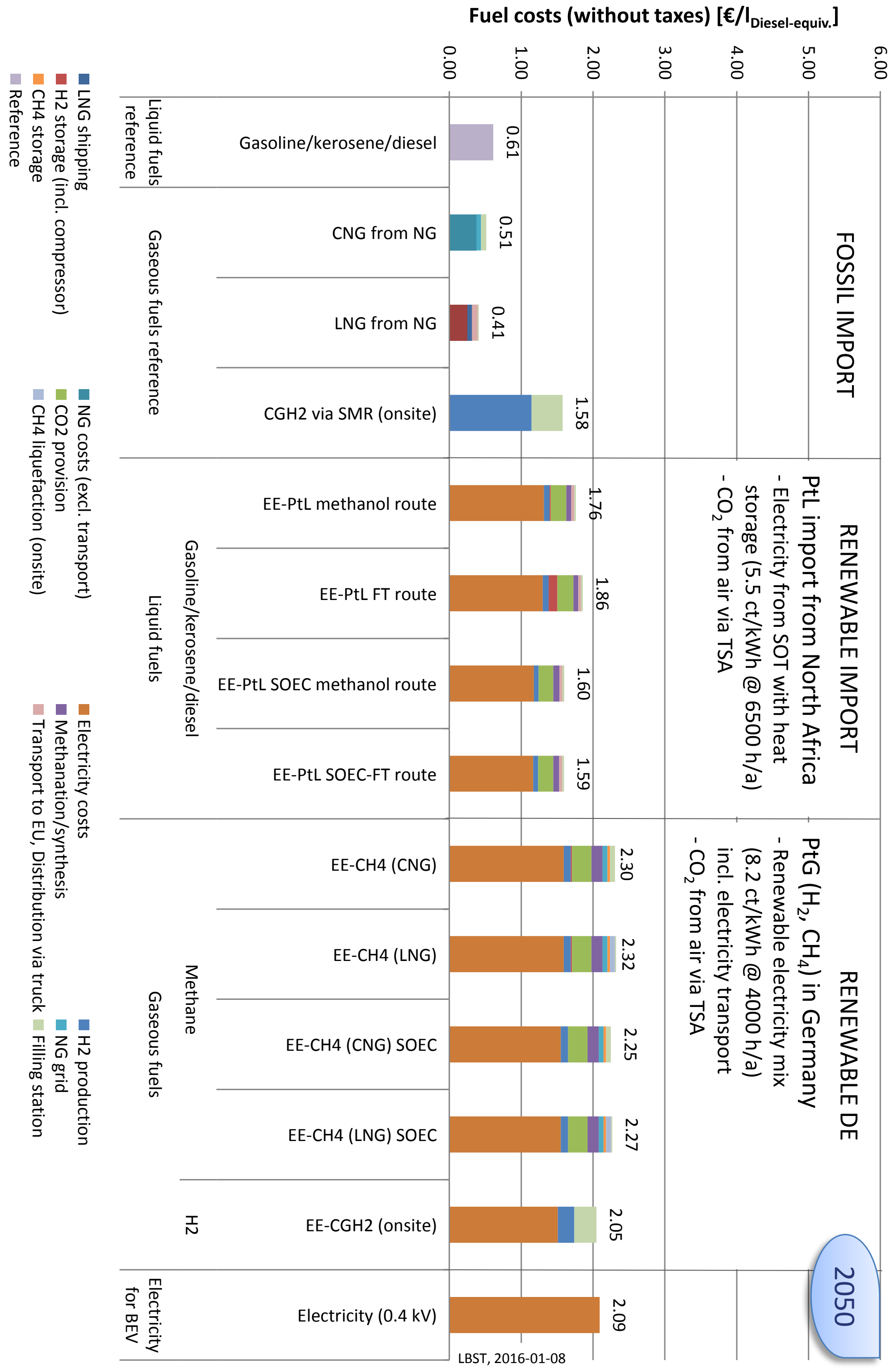
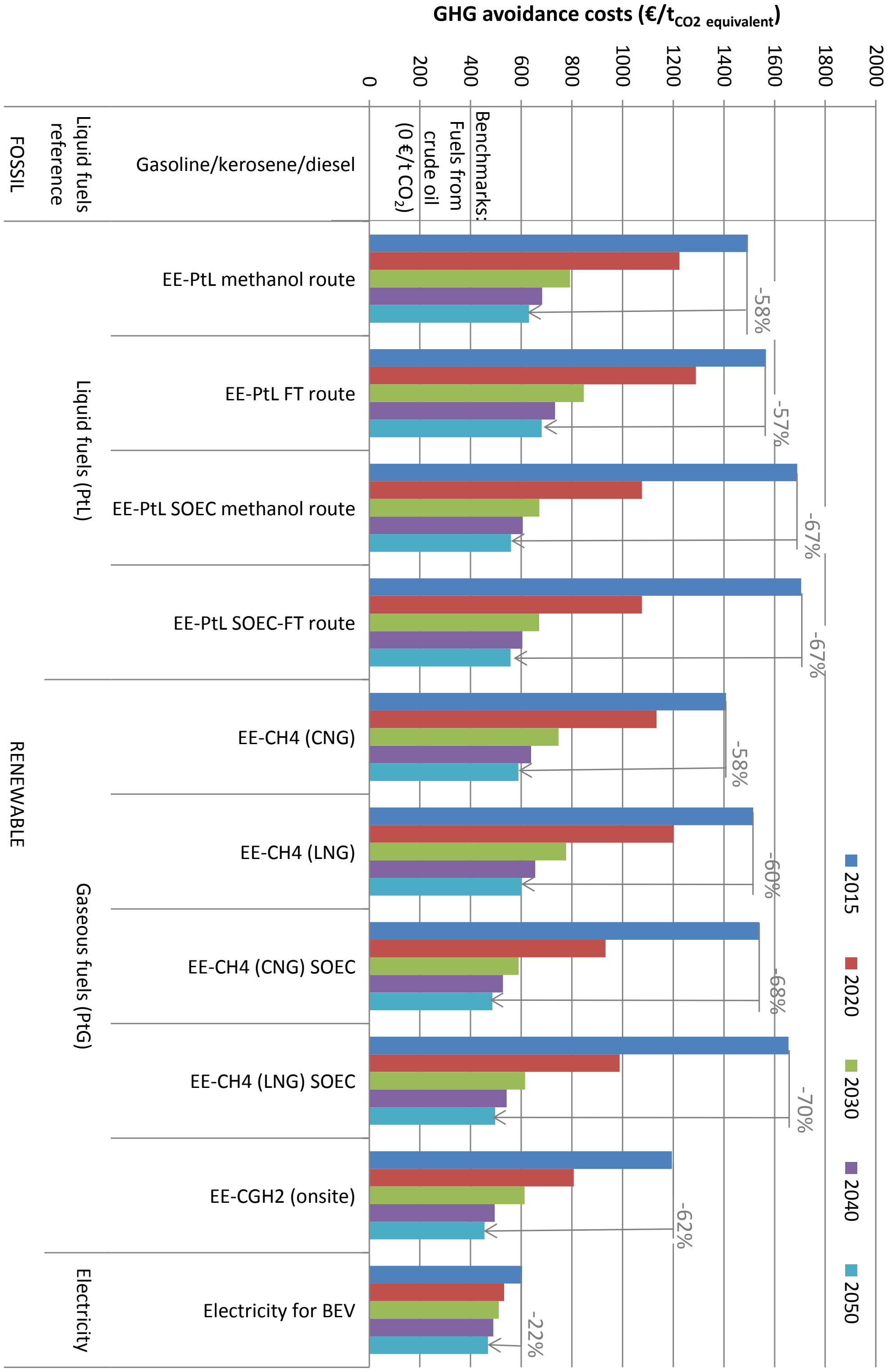


Figure 44: **Specific fuel costs (including PtL imports), 2050, EU**



LBST, 2016-01-08

Figure 45: GHG avoidance costs (€/t$_{CO2\text{-}equiv.}$), PtX fuels, EU

5.3 Developments of vehicle/powertrain specific consumption

This chapter gives an overview over vehicle specific consumption assumptions for the following vehicle categories and propulsion systems respectively:

- Cars: internal combustion engine (incl. ICE-hybrid and ICE-REEV), battery, fuel cell
- Trucks: internal combustion engine incl. hybrid and REEV, battery, fuel cell
- Bus: internal combustion engine, battery, fuel cell
- Train: internal combustion engine, fuel cell
- Ship: gas engine
- Aircraft: gas turbine, fuel cell

5.3.1 Passenger transport

5.3.1.1 Passenger vehicle

The evolution of the fuel consumption of passenger cars has been derived from the expected evolution of the fuel consumption of a vehicle of the C-segment (e.g. VW Golf, Ford Focus).

The fuel consumption of conventional gasoline and diesel vehicles for 2015 and the evolution until 2020 have been derived from data in [Spritmonitor 2015]. The fuel consumption of the conventional CNG vehicle in 2015 has been derived from [Spritmonitor 2015].

The gasoline consumption data for the gasoline fuelled range extender electric vehicle (REEV) for 2015 has been derived from [Opel 2014] plus addition for real world fuel consumption, the electricity consumption from [Spritmonitor 2015]. The diesel consumption of the diesel fueled REEV has been derived from the gasoline REEV by multiplication with a factor derived from [JEC 2014].

Analogous to the regulation it has been assumed that from 2020 new cars (fleet) have to meet the CO_2 emission limit of 95 g/km during the New European Driving Cycle (NEDC) and that in 2035 full market penetration of these vehicles has occurred. The emission factor of gasoline amounts to about 73.3 g/MJ of gasoline. As a result a passenger vehicle which meets the CO_2 emission limit of 95 g/km consumes about 1.295 MJ/km (0.360 kWh/km or about 4.0 l of gasoline per 100 km). The real world fuel consumption is about 25% higher leading to about 1.62 MJ/km (0.450 kWh/km or about 5.0 l of gasoline per 100 km).

The diesel consumption of the conventional vehicle with internal combustion engine (ICE) in 2035 has been derived from the ratio between gasoline and diesel engine indicated in [JEC 2014] multiplied with the fuel consumption of the conventional gasoline ICE vehicle.

For 2050 a slightly further decrease of fuel consumption has been assumed for the conventional gasoline and diesel vehicles because of the introduction and market penetration of an improved start-stop systems i.e. the 48 V system 'Eco Drive' developed by Continental [Bilo 2014].

For CNG it has been assumed that the fuel consumption is 3% lower than that of the gasoline ICE vehicle.

According to [IKA 2014] the gasoline consumption of hybrid electric vehicles (HEV) is about 26.5% lower than those of the conventional vehicle with internal combustion engine (ICE). In case of diesel passenger vehicles the fuel consumption is 23.5% lower than those of the conventional diesel vehicle. In case of CNG it has been assumed that the fuel consumption is 25% lower than that of the conventional CNG vehicle. For HEV analogous to [ICCT et al 2014] it has been assumed that the real world fuel consumption is 40% higher than that measured over the NEDC.

For battery electric vehicles (BEV), range extender electric vehicles (REEV) and fuel cell vehicles (FCEV) it has assumed that the real world final energy consumption is 40% higher than the NEDC values except for 2015 where measured real world values have been used. For 2015 the final energy consumption of the BEV has been derived from [Spritmonitor 2015].

Table 49 shows the real world fuel consumption of passenger vehicles from the C-segment.

Table 49: Fuel consumption – cars (MJ/km)

Vehicle	2015e	2020	2030	2040	2050
ICE-Gasoline	2.4	2.17	1.8	1.62	1.61
ICE-Diesel	2.0	1.94	1.55	1.35	1.34
ICE-Methane	2.52	2.1	1.75	1.57	1.57
Hybrid-Gasoline	1.98	1.78	1.48	1.33	1.33
Hybrid-Diesel	1.71	1.66	1.32	1.15	1.15
Hybrid-Methane	2.12	1.76	1.47	1.32	1.32
REEV-Gasoline (gasoline)	0.54	0.41	0.36	0.34	0.34
REEV-Gasoline (electricity)	0.59	0.58	0.5	0.46	0.46
REEV-Diesel (diesel)	0.53	0.4	0.36	0.33	0.33
REEV-Diesel (electricity)	0.59	0.59	0.5	0.46	0.46
REEV-Methane (gas)	0.57	0.39	0.35	0.33	0.33
REEV-Methane (electricity)	0.59	0.58	0.5	0.46	0.46
BEV	0.6	0.6	0.56	0.53	0.53
FCEV	1.44	1.05	0.85	0.75	0.75

5.3.1.2 Buses

The fuel consumption of the diesel and CNG fuelled buses in 2015 has been derived from [VTT 2012]. The fuel consumption of the fuel cell (FCEV) in 2015 has been derived from measured data for the Daimler Citaro FuelCELL hybrid [EvoBus 2009]. For the evolution of the fuel consumption in the future it has been assumed that the fuel consumption decreases with the same percentage as that of heavy trailer trucks.

Table 50: Fuel consumption – buses (MJ/km)

Vehicle	2015e	2020	2030	2040	2050
ICE-Diesel	15.2	13.6	12.1	11.4	10.8
ICE-Methane	21.5	18.6	15.7	15.5	15.4
FCEV	14.4	14.0	13.5	12.5	11.4

5.3.1.1 Trains

The typical train-size for long-distance rail transport was chosen as one ICE-unit with typically 430 seats in average (for Details see Annex B). Long-distance trains are almost 100% electrically driven.

The electricity consumption of high speed trains for long distance rail transport strongly depends on the speed. New railway allows a higher speed leading to higher electricity consumption. On the other hand the new model 'ICE 3' consumes less electricity than older ones (e.g. 'ICE 1'). The ICE 3 has been introduced in 1997.

According to [IFEU 2011] the electricity consumption of ICE ranges between 0.029 and 0.034 kWh per seat and km depending on the speed based on data from DB AG in 2010. With 430 seats the electricity consumption would amount to about 45 to 53 MJ per train-km.

Table 51 shows the electricity consumption of high speed trains according to [Ilgmann 1998], [DB 2010], and [IFEU 2011].

Table 51: Electricity consumption long distance high speed trains (MJ/km)

	ICE 1 'Line 6' (13 rail cars)	ICE 1 'Line 4' (11 rail cars	ICE 1'Line 3' (10 rail cars)	ICE 3	ICE (mix)
New railway	103	90	88	n. d. a.	53
Old railway	77	68	67	n. d. a.	45
Average	87	77	72	72	n. d. a

In this study an electricity consumption of 72 MJ/train-km has been used for the long distance high speed train.

Short distance trains can be distinguished between suburb trains (which are called 'S-Bahn' in Germany) and other short distance trains used in rural areas and for the transport between smaller cities (cities with less than 50,000 inhabitants).

Today, for suburb trains mainly model ET 423 and ET 430 with a capacity of 184 and 192 seats respectively [DB 2014] plus 296 standing are used. The ET 423 and ET 430 are used as suburb train ('S-Bahn'). According to [IFEU 2011] the electricity consumption of the 'S-Bahn' is indicated with 0.026 kWh per km and capacity (seats and standing) leading to about 45 MJ per train-km. The diesel version consumes 6.0 g of diesel per km and capacity (seats and standing) leading to about 124 MJ per train-km.

For trains other than suburb trains often diesel fueled rail cars like 'VT 610' with a capacity of 120 seats has been used. In [IFEU 2011] the electricity consumption for short distance trains of the Deutsche Bahn AG excluding suburb trains is indicated with 0.031 kWh per seat leading to about 13 MJ per train-km if the number of seats is assumed to be 120. The diesel consumption is indicated with 6.5 g per km and seat leading to about 34 MJ/km if the number of seats is assumed to be 120. In [Bucher 1998] the diesel consumption of the rail car 'VT 610' is indicated with 1 l per km leading to about 36 MJ/km which is close to the 34 MJ per km derived from [IFEU 2011]. In [Bucher 1998] the fuel consumption of a hydrogen fueled fuel cell rail car based on 'VT 610' is indicated with 5,000 l of liquid hydrogen per 2,000 km leading to about 21 MJ per km.

Table 51 shows the final energy consumption of various short distance trains.

Table 52: Final energy consumption of short distance trains

	Unit	S-Bahn (electricity)	S-Bahn (diesel)	RE/RB/IRE (electricity)	VT 610 (diesel)	VT 610 (H_2)
Number of seats	-	184	184	120*	120	120
Number of standing	-	296	296	-	-	-
Total	-	480	480	120	120	120
Electricity	MJ/km	45	-	13	-	-
Diesel	MJ/km	-	124	-	34-36	-
Hydrogen	MJ/km	-	-	-	-	21
Occupancy		29.8%	29.8%	23.1%	23.1%	23.1%

*Assumption to convert the MJ per km and seat to MJ per train-km

For short distance train the fuel consumption data of a rail car with 120 seats has been chosen.

Concerning future improvements, [DB 2013] specifies that electric driven trains can save up to 14% of electricity due to brake-energy-regeneration in short distance transport and 11% in long-distance transport. This potential is almost exhausted as all new electric trains possess a regeneration system. On the other hand elevation of speed leads to an increase of the electricity consumption of long distance high speed. Therefore, it has been assumed that the specific energy consumption for long distance trains is constant over time.

Table 53 shows the final energy consumption of trains used for the scenarios.

Table 53: Fuel consumption – trains (MJ/km)

Vehicle	2015e	2020	2030	2040	2050
Rail car (electricity)	13	13	13	12	11
Rail car (diesel)	36	35	33	32	30
Rail car (H_2)	21	21	20	19	18
Trains long-distance	72	72	72	72	72

5.3.1.2 Aircraft

According to [LH 2014] the average fuel consumption of the LH fleet in 2013 was 3.91 liter per 100 pkm. As the utilisation rate was 82% this translates to 3.21 l/100 seat-km. The average aircraft size was calculated with 170 seats (see Annex B). This results in an average fuel consumption of 5.32 l/km. With the energy content of 34.4 MJ/l this translates into 188 MJ/aircraft-km.

However, using the data from [LH 2014] does not lead to the overall fuel consumption of 375 PJ for aviation in Germany in 2013 indicated in [VIZ 2014/2015]. According to [BVU et al 2014] the average fuel consumption of aircraft in Germany and air craft leaving Germany was about 43.9 g of kerosene per pkm or about 5.46 l per 100 pkm. In [DFS 2015] the average seat occupancy of aircraft was indicated with about 73% in 2010 and the decrease of fuel consumption due to technology improvement was indicated with 1% per year. At a lower heating value (LHV) of 42.8 MJ per kg of kerosene and 170 seats per aircraft the fuel consumption of a typical aircraft in 2015 would be about 222 MJ per aircraft-km. This number has been used for the scenarios.

For the calculation of the future consumption an efficiency improvement of 1.5% per year until 2020 and of 0.57% until 2030 is assumed.

The fuel consumption for liquefied hydrogen (LH_2) fuelled fuel cell (FC) aircraft is calculated from the specification of 192 MJ/km for an aircraft which conventionally fuelled would consume 214 MJ/km. Scaling with the unit size aircraft the consumption of 184 MJ is calculated for 2015.

Table 54: Fuel consumption – aircraft (MJ/km)

Vehicle	2015e	2020	2030	2050
Kerosene aircraft	222	206	194	194
LH_2 fuelled FC aircarft	199	184	175	175

The average occupancy increases from 73% in 2010 to 82% in 2020.

5.3.2 Cargo transport

5.3.2.1 Road

The diesel consumption for diesel fuelled trucks and the fuel consumption of the other trucks after 2015 has been derived from [Kreyenberg et al 2015] which are partly based on [NANUPOT 2011].

The fuel consumption of the small (< 3.5 t maximum gross weight) and medium (3.5 to 12 t maximum gross weight) NG fueled trucks with internal combustion engine (ICEV) and the H_2 fuelled trucks with fuel cell technology (FCEV) for 2015 has been derived from [NANUPOT 2011].

The fuel consumption of the medium (3.5 to 12 t maximum gross weight) has been derived from a weighted average of truck with a maximum gross weight of 3.5 to 7.5 t and 7.5 to 12.0 t.

Tests with LNG fuelled heavy trailer truck (IVECO Stralis LNG) lead to a fuel consumption of about 28 kg of LNG per 100 km leading to about 14 MJ/km [Hendrickx 2014]. The fuel consumption of the fuel cell heavy trucks (>12 t maximum gross weight) has been derived from [SCAQMD 2012a].

Table 55: Fuel consumption – road (MJ/km)

Vehicle	1995	2015	2020	2030	2040	2050
ICE-Diesel < 3.5 t	4.0	3.0	2.6	2.2	2.1	1.9
ICE-Methane < 3.5 t	5.0	3.7	3.1	2.4	2.3	2.2
FCEV < 3.5 t	-	1.4	1.3	1.3	1.3	1.2
ICE-Diesel 3.5-12 t	7.0	6.0	5.4	4.9	4.6	4.3
ICE-Methane 3.5-12 t	9.0	7.8	7.0	6.3	5.8	5.4
FCEV 3.5-12 t	6.0	4.6	4.2	3.9	3.6	3.2
ICE-Diesel > 12 t	13.0	11.1	10.0	8.8	8.4	7.9
ICE-Methane > 12 t	16.0	14.0	12.1	10.2	10.1	10.0
FCEV > 12 t	-	7.5	7.2	7.0	6.5	5.9

5.3.2.2 Railway

The fuel consumption is calculated from MJ/tkm data and translated to trains with a typical capacity of 532 t/train. From [DB 2002] results, that the share of electro-traction on final energy consumption changed between 1993 and 2002 from 53 to 60%. The data are explicitly provided for 2002 and 2003: Share of electro-traction on final energy consumption of passenger transport rose from 68 to 71%; the share of electro-traction on final energy consumption of goods transport was about 68%. The published data are met by the assumption that the share of diesel-traction on tkm is 20%, and with the specific final energy consumption of 0.157 MJ of electricity per tkm, and 0.306 MJ of diesel fuel per tkm. This translates in a typical final energy consumption of 83.5 MJ/train-km (electricity) and 163 MJ/train-km (fuel). As the empty-km are already included in the calculation of the specific energy consumption, these are not explicitly accounted for.

In [DB 2003] the conversion-factor from primary energy to final energy is 0.28 for electricity and 0.88 for diesel fuel. It is assumed that the share of diesel and the specific energy consumption factors for diesel and electricity are still valid, but that the conversion efficiency of electricity production has improved. However, this is discussed elsewhere. Concerning future improvements, [DB 2014] specifies that electric driven trains can save about 6% of energy by use of energy-regeneration from braking.

For diesel fueled engines no brake-energy-regeneration takes place.

[DB 2014] exhibits only the average specific primary energy consumption with 0.37 MJ/tkm.

For the hydrogen consumption of the fuel cell train it has been assumed that the ratio between the fuel consumption of the diesel fuelled train and that of the hydrogen fuelled fuel cell train is the same as in case of passenger transport.

Table 56: Fuel consumption – rail (MJ/km)

Vehicle	1995	2015	2020	2030	2040	2050
Train (OHL electric)	100	83.5	83	83	83	83
Train (Diesel)	170	163	160	155	155	155
Train (H_2 FCEV)	101	96	95	92	92	92

5.3.2.3 Inland navigation and maritime transport

The fuel consumption of inland barges are calculated from MJ/tkm data and up-scaled to barges with a typical capacity of 1,290 t (inland) respectively 35,000 t).

[BVB 2005] published the typical fuel consumption on German inland waterways with 0.464 MJ/tkm, based on a study from IFEU in 1992. [Planco 2007] updated the data in a full cost comparison of various transport vectors to between 0.140 – 0.310 MJ/tkm with average of 0.230 MJ/tkm. These data are used by BVB in the annual reports 2007-2014. This is almost equal for inland bulk carriers and containerships. For Austria [bmvit 2015] publishes an average consumption of 0.335 MJ/tkm. As these data are primary energy based, the final energy consumption is about 10% lower. For the scenario calculations, the average figure of 0.230 MJ/tkm (PEV), respectively 0.207 MJ/tkm (final energy consumption) is chosen. This adds to 267 MJ/vessel-km. [Planco 2007] estimates that the future energy consumption still can be reduced by about 20%. For the calculation a conservative improvement of about 10% is assumed.

The average fuel consumption of oversea freight vessels is assumed with 2.5 g/tkm (3 g/tkm in 1995), respectively with the energy content of 43 MJ/kg, with 0.107 MJ/tkm. For a 35,000 t-ship this adds to 3745 MJ/vessel-km.

For methane (CNG/LNG) and methanol (MeOH) propelled ships an energy consumption similar to diesel ships is assumed.

Table 57: Fuel consumption – ships (MJ/km)

Vehicle	1995	2015	2020	2030	2040	2050
Inland – Diesel (1,290t)	600	267	260	245	242	240
Inland – Methane (1,290t)	600	267	260	245	242	240
Inland – Methanol (1,290t)	600	267	260	245	242	240
Oversea – Diesel (35,000t)	4515	3745	3700	3700	3700	3700
Oversea – Methane (35,000t)	4500	3745	3700	3700	3700	3700
Oversea – Methanol (35,000t)	4500	3745	3700	3700	3700	3700

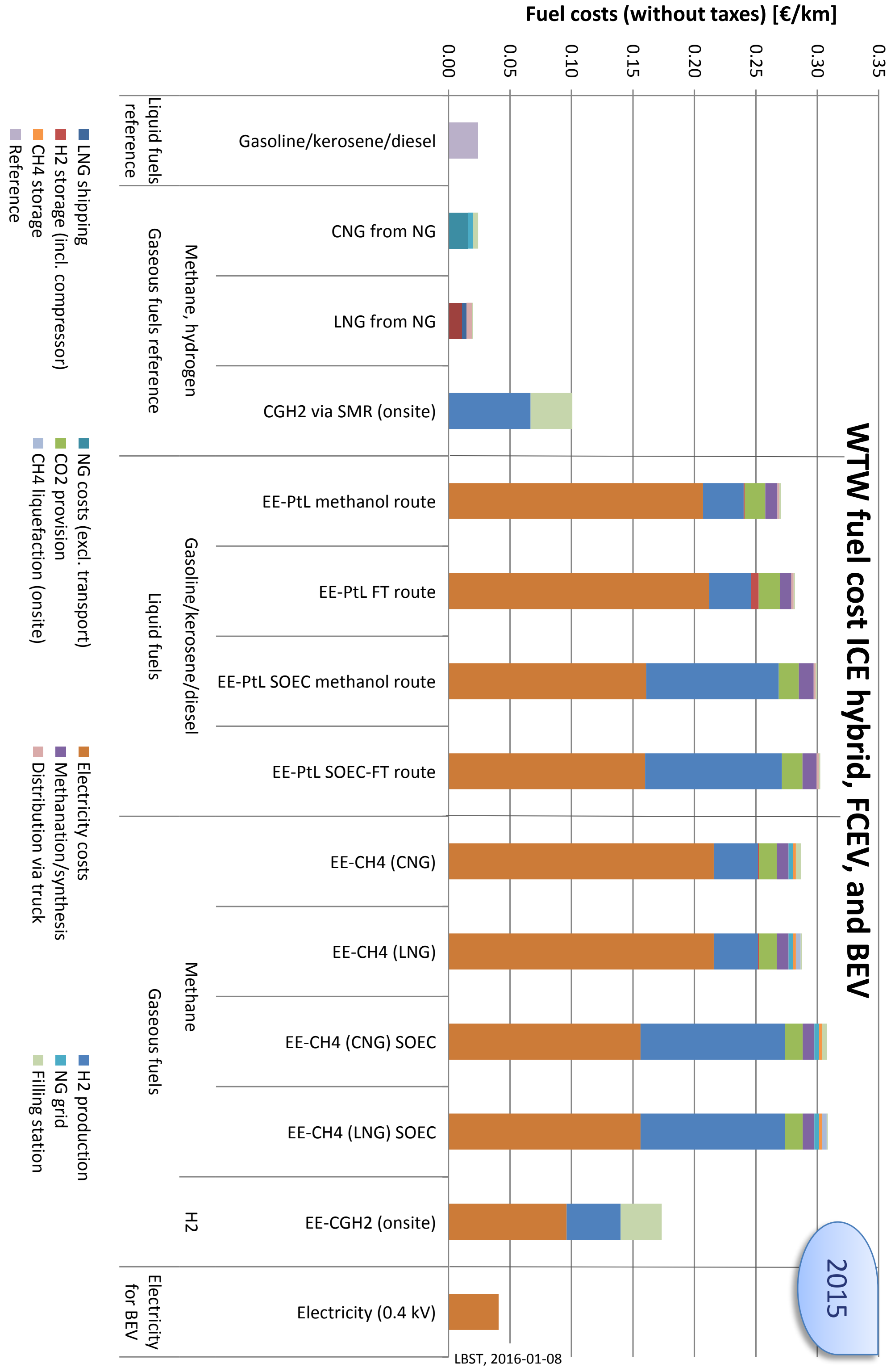
5.4 Results fuel costs ‘well-to-wheel‘ for passenger vehicles

Based on the assumptions as laid out in chapter 5.1 and chapter 5.3 the following specific fuel costs ‘well-to-wheel’ result for Germany and EU-28 respectively.

For this cost comparison, a reference car from the C segment (e.g. Audi A3, BMW 1er, Ford Focus, Mercedes A-Klasse, Opel Astra, Toyota Auris, VW Golf) has been used.

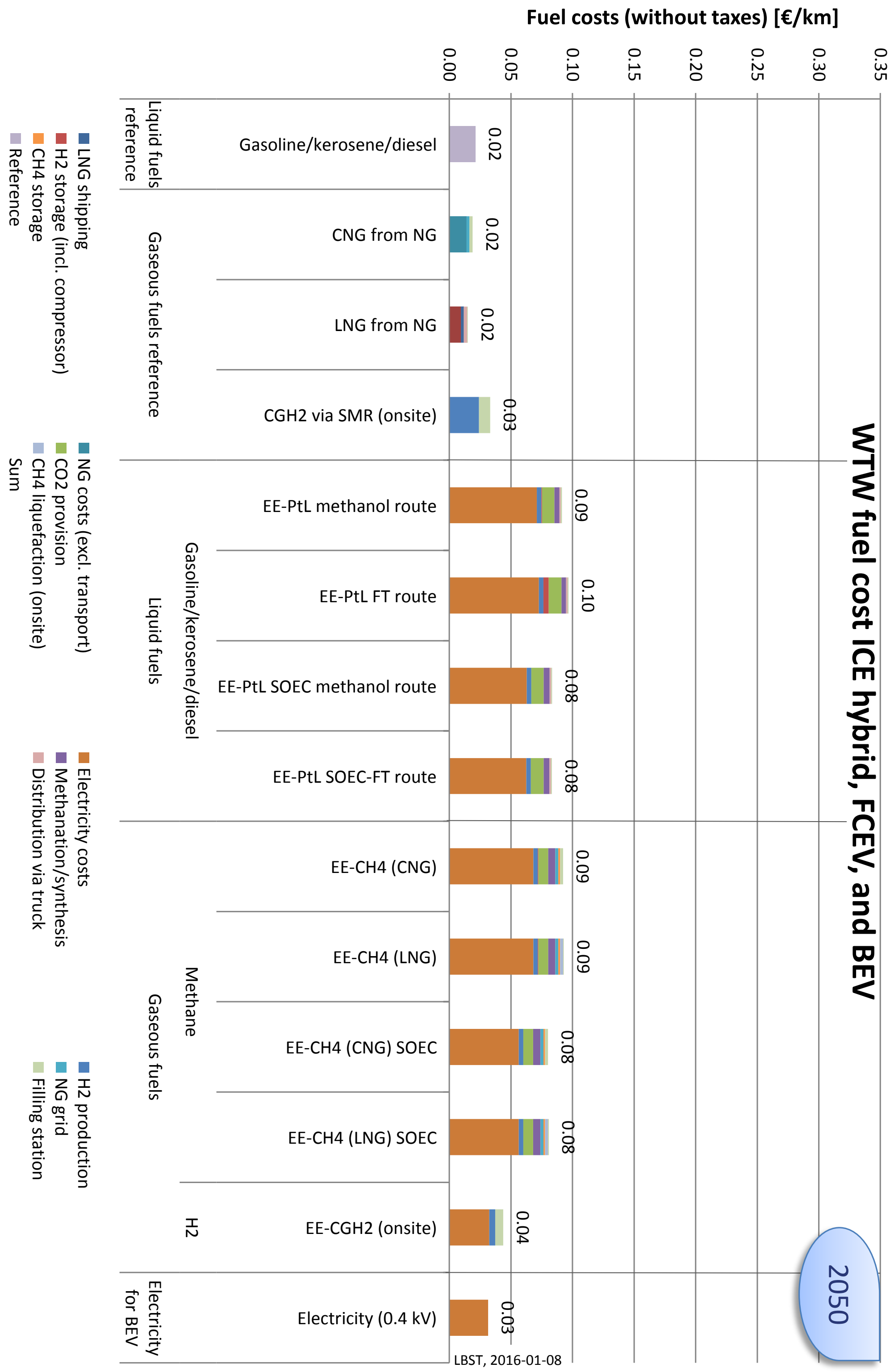
For liquid transportation fuels a mix of gasoline and diesel hybrid vehicles has been used. For methane, hybrid vehicles with gas engines (Otto cycle) and for hydrogen, fuel cell electric (FCEV) vehicles have been used.

a) Germany



LBST, 2016-01-08

Figure 46: **Fuel costs ‘well-to-wheel’ passenger cars (domestic electricity and PtX production), 2015, Germany**



LBST, 2016-01-08

Figure 47: **Fuel costs 'well-to-wheel' passenger cars (domestic electricity and PtX production), 2050, Germany**

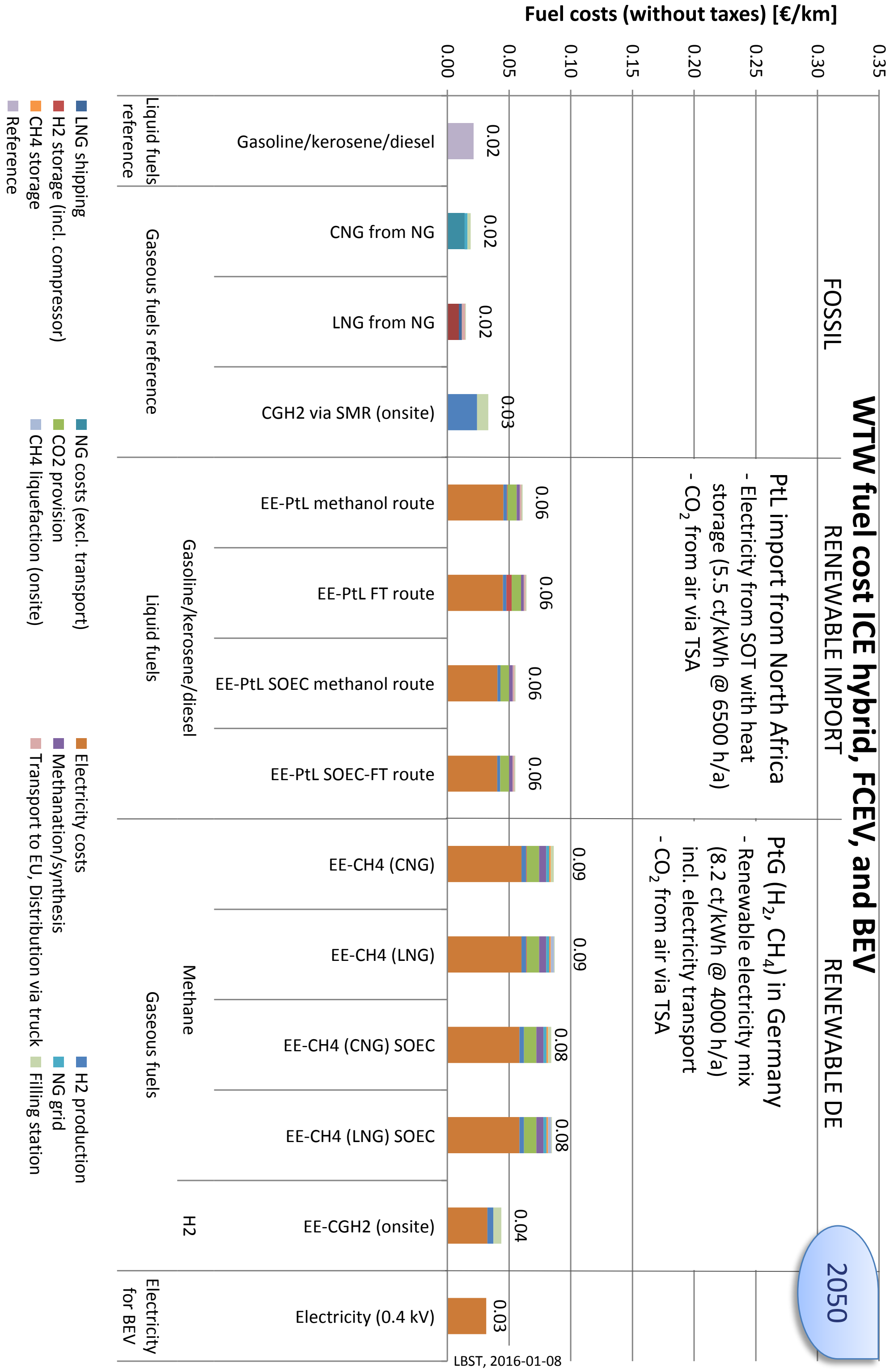


Figure 48: Fuel costs ‘well-to-wheel’ passenger cars (import PtL compared with domestic electricity and PtG), 2050, Germany

b) Europe

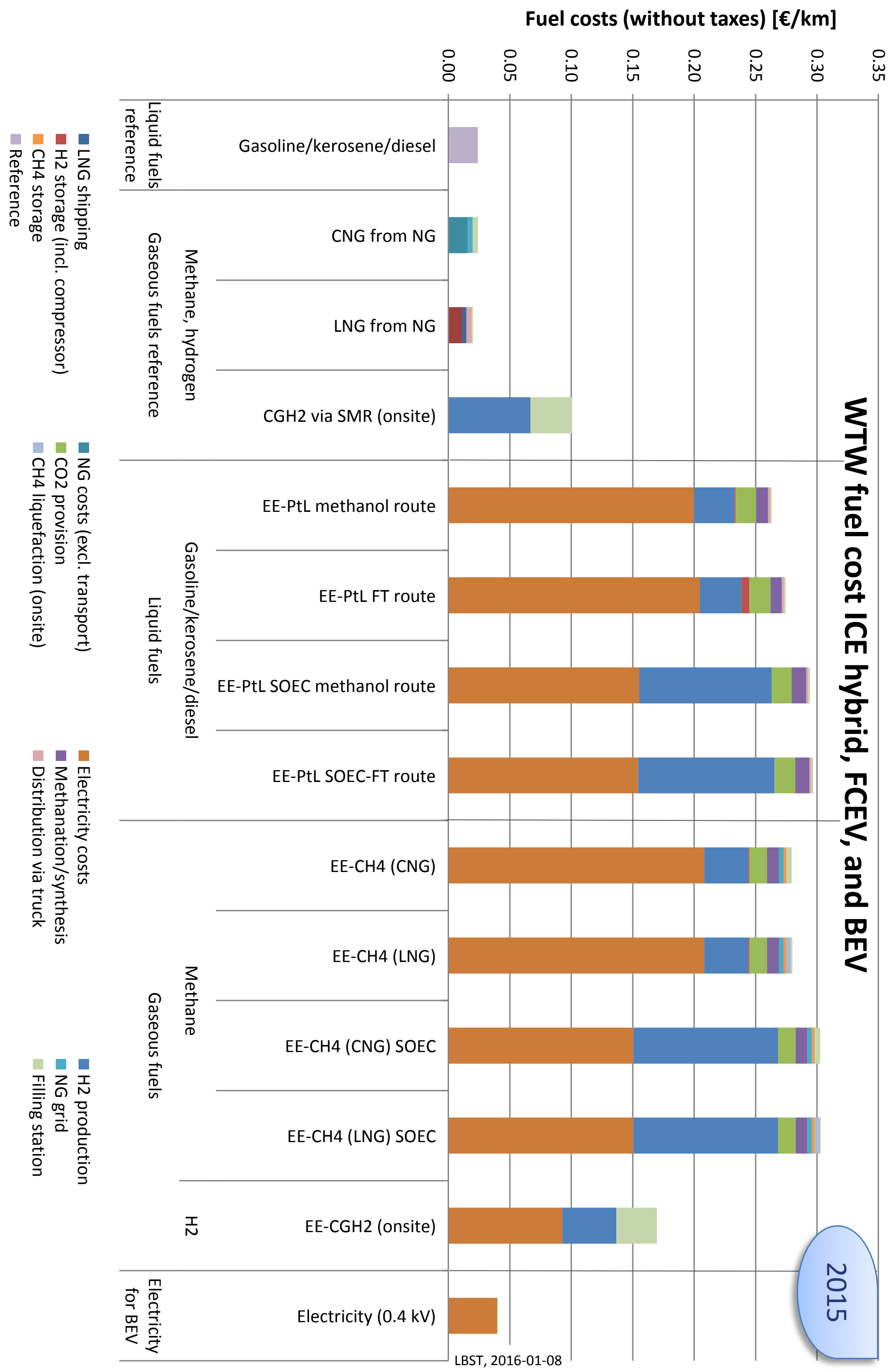


Figure 49: Fuel costs 'well-to-wheel' passenger cars (domestic electricity and PtX production), 2015, EU

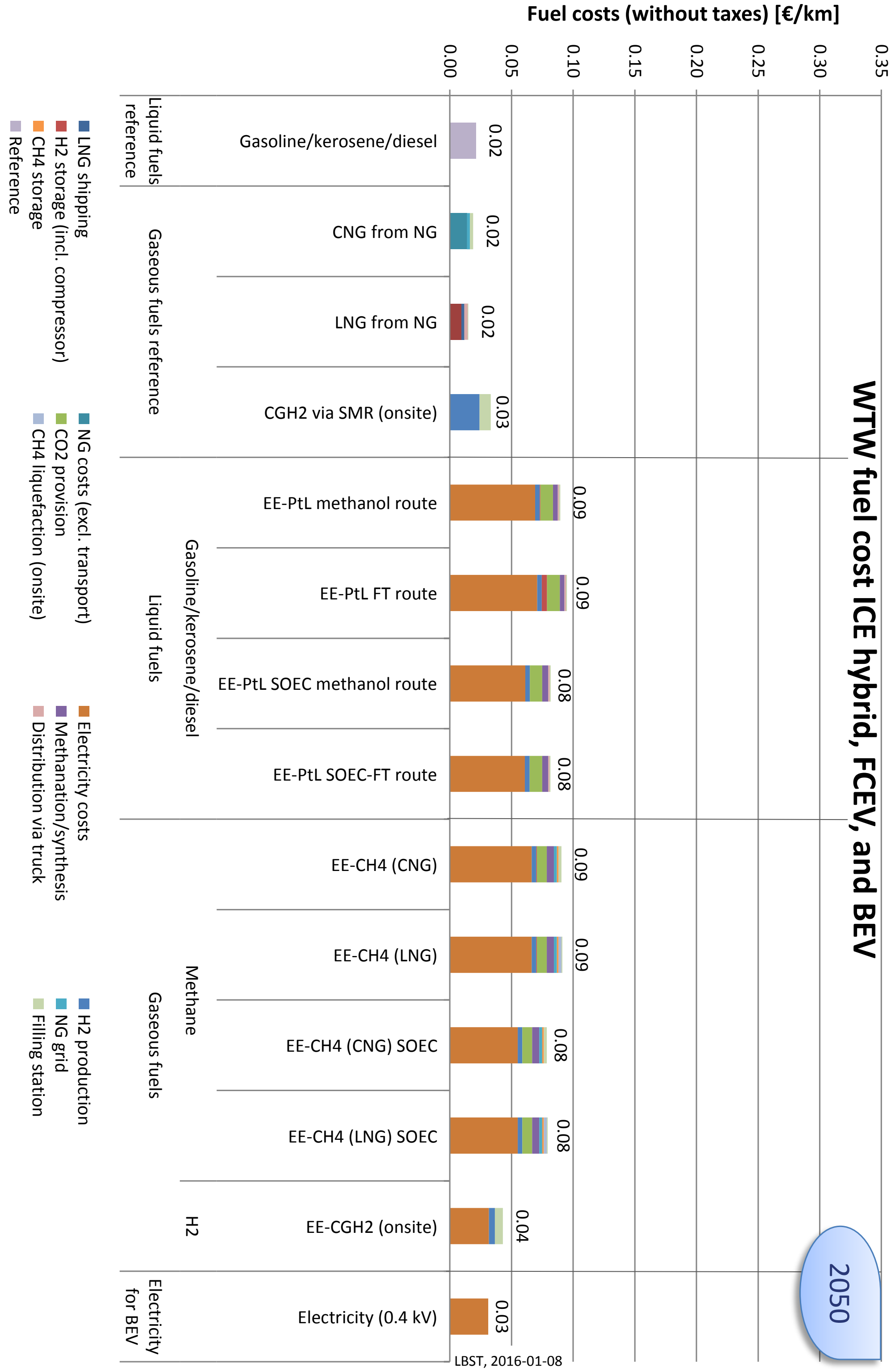


Figure 50: Fuel costs 'well-to-wheel' (domestic electricity and PtX production), 2050, EU

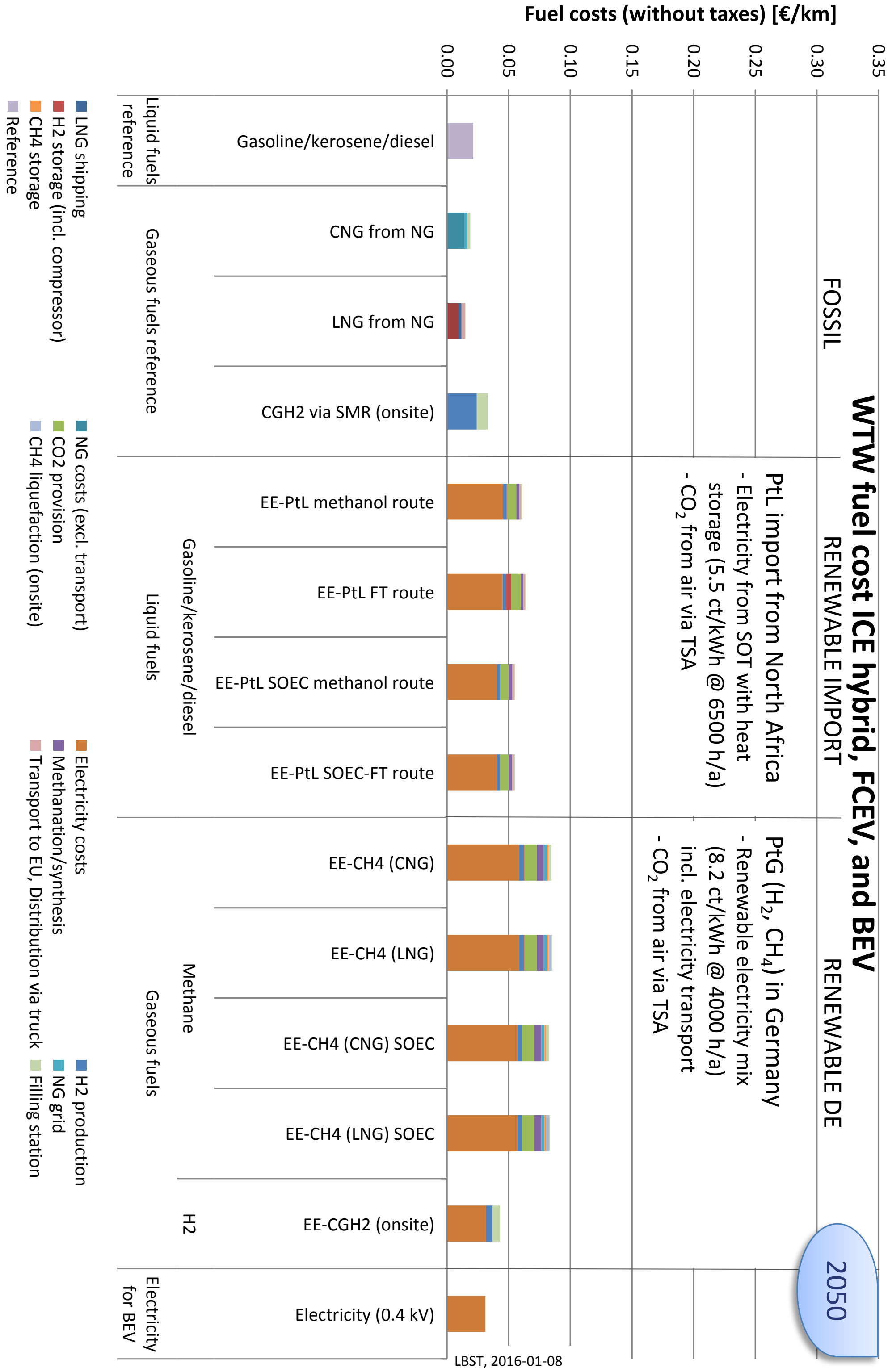


Figure 51: Fuel costs 'well-to-wheel' passenger cars (import PtL compared with domestic electricity and PtG), 2050, EU

6 DEFINITION OF THREE FUEL & POWERTRAIN SCENARIOS

When developing fuel/powertrain scenarios of the future, basic scenario considerations apply with regard to trade-offs between adequate levels of comprehensiveness, detail, complexity, transparency, and data certainty. In order to strike the balance, the fuel/powertrain options as shown in Table 58 have been taken into account.

Table 58: Overview over fuels and powertrains considered in this study, depicted by transport mode

	Turbine	ICE / hybrid	ICE-REEV	FCEV	BEV	OHL
Cars	-	☑ gasoline, diesel, methane	☑ gasoline, diesel	☑	☑	-
Trucks	-	☑ diesel, methane	-	☑	☑	-
Buses	-	☑ diesel, methane	-	☑	☑	-
Trains	-	☑ diesel	-	☑	-	☑
Ships	-	☑ diesel, methane, methanol	-	-	-	-
Aircrafts	☑ kerosene	-	-	☑	-	-

For the purpose of scoping possible future energy demands – and its associated costs, investments, and greenhouse gas emissions – two archetype/boundary scenarios have been agreed with the FVV working group members, including one mix scenario that was postulated to lie somewhere in between the two extremes. Scenarios 1 and 3 represent a maximum and minimum energy demand to serve the transportation demand as led out in the two transportation demand scenarios (HIGH and LOW) in the preceding chapter 4. Scenario 2 is to serve only the LOW transportation demand scenario because only these 'scenario worlds' are compatible to each other.

The fuel/powertrain scenarios are represented in terms of percentage-shares of newly registered vehicles in the respective scenario year. In the transportation model, scenario step years are interpolated and annual vehicle fleet changes are calculated.

Furthermore, the vehicle market is global. While fuel/powertrain mixes between world regions may differ significantly, the same fuel/powertrain scenarios have been applied for Germany and the EU for the purpose of this study.

The scenario characteristics are described in the following chapters. The fuel/powertrain mixes for the different transportation modes are detailed in tables; therein, the scenario 'centres of gravity' are highlighted in yellow background color to give a quick orientation. Graphical presentation is given for car and truck data. For the resulting energy, emissions, costs, and cumulated investments, see chapter 7.

6.1 «PTL» scenario

Conservative scenario based on well-established fuels, powertrains and infrastructures. Combustion engines continue to play the dominant role. Regulatory-induced powertrain efficiency improvements are assumed until 2020. Power-to-liquids replace today's fossil fuels. – This scenario could be seen as 'business-as-usual' case.

Table 59: Car mix of new registrations in the «PTL» scenario

CAR [%]	ICE Gasol./ Diesel	ICE Methane	Hybrid Gasol./ Diesel	Hybrid Methane	REEV Gasol./ Diesel	REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	80	0	20	0	0	0	0	0
2030	40	0	60	0	0	0	0	0
2040	10	0	90	0	0	0	0	0
2050	0	0	100	0	0	0	0	0

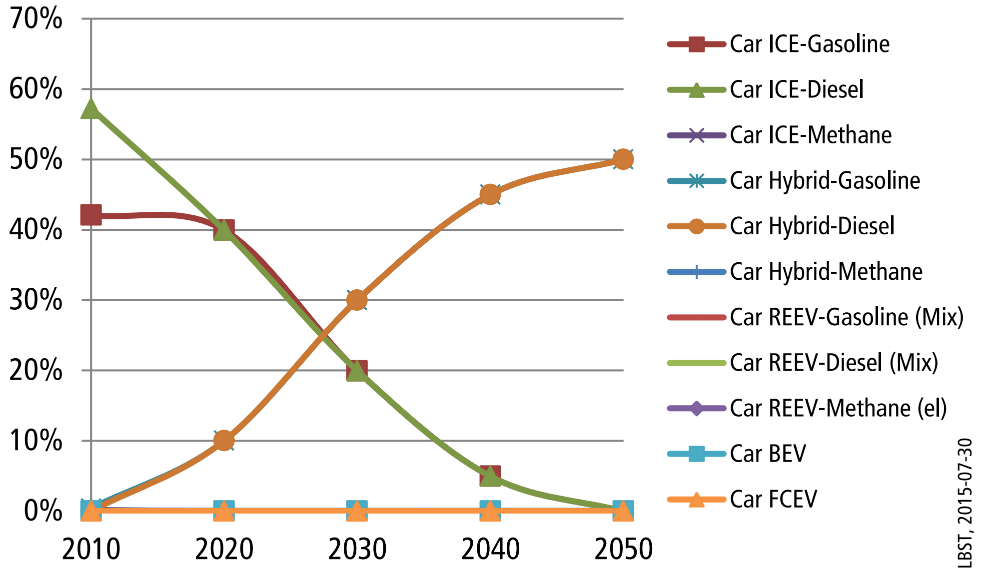


Figure 52: Car deployment «PTL» 2010-2050 in % of new registrations

Table 60: Truck mix of new registrations in the «PTL» scenario

TRUCK [%]	Truck <3.5t			Truck 3.5-12t			Truck/Trailer>12t		
	Diesel	BEV	FCEV	Diesel	Methane	FCEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	100	0	0	100	0	0	100	0	0
2030	100	0	0	100	0	0	100	0	0
2040	100	0	0	100	0	0	100	0	0
2050	100	0	0	100	0	0	100	0	0

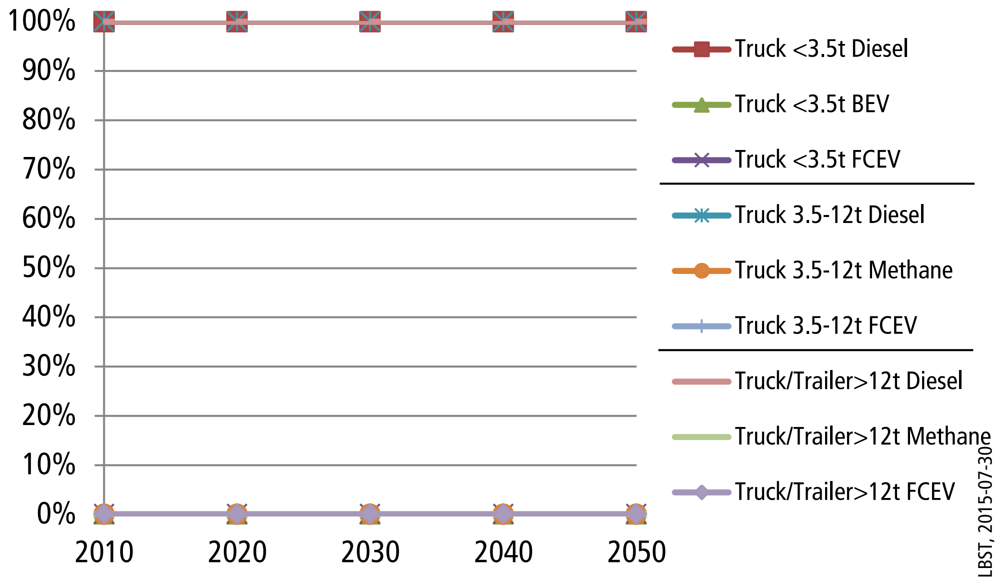


Figure 53: Truck deployment «PTL» 2010-2050 in % of new registrations

Table 61: Bus mix of new registrations in the «PTL» scenario

BUS [%]	ICE Diesel	ICE Methane	FCEV
2010	99	1	0
2020	97	3	0
2030	95	5	0
2040	95	5	0
2050	95	5	0

Table 62: Train mix of new registrations in the «PTL» scenario

TRAIN [%]	Passenger			Freight		
	Electricity (OHL)	Diesel	H_2	Electricity (OHL)	Diesel	H_2
2010	80	20	0	80	20	0
2020	80	20	0	80	20	0
2030	80	20	0	80	20	0
2040	80	20	0	80	20	0
2050	80	20	0	80	20	0

Table 63: Ship mix of new registrations in the «PTL» scenario

SHIP [%]	Inland waterway			Maritime		
	Diesel	Methane	Methanol	Diesel	Methane	Methanol
2010	100	0	0	100	0	0
2020	99	0	1	98	0	2
2030	95	0	5	90	0	10
2040	91	0	9	82	0	18
2050	90	0	10	80	0	20

Table 64: Plane mix of new registrations in the «PTL» scenario

PLANE [%]	Kerosine	LH_2-FC
2010	100	0
2020	100	0
2030	100	0
2040	100	0
2050	100	0

6.2 «FVV» scenario

The 'FVV scenario' consists of a balanced portfolio of established and novel fuels, powertrains, and respective infrastructures. A mix of currently discussed options, comprising ambitious energy efficiency improvements of powertrains with internal combustion engines beyond 2020, including hybrids, REEV, BEV, FCEV as well as improved turbine propulsion systems in aviation has been taken into account.

Table 65: Car mix of new registrations in the «FVV» scenario

CAR [%]	ICE Gasol./ Diesel	ICE Methane	Hybrid Gasol./ Diesel	Hybrid Methane	REEV Gasol./ Diesel	REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	36	5	45	2	6	0	4	1
2030	0	0	55	5	25	0	10	5
2040	0	0	37	2	45	0	16	9
2050	0	0	0	0	70	0	20	10

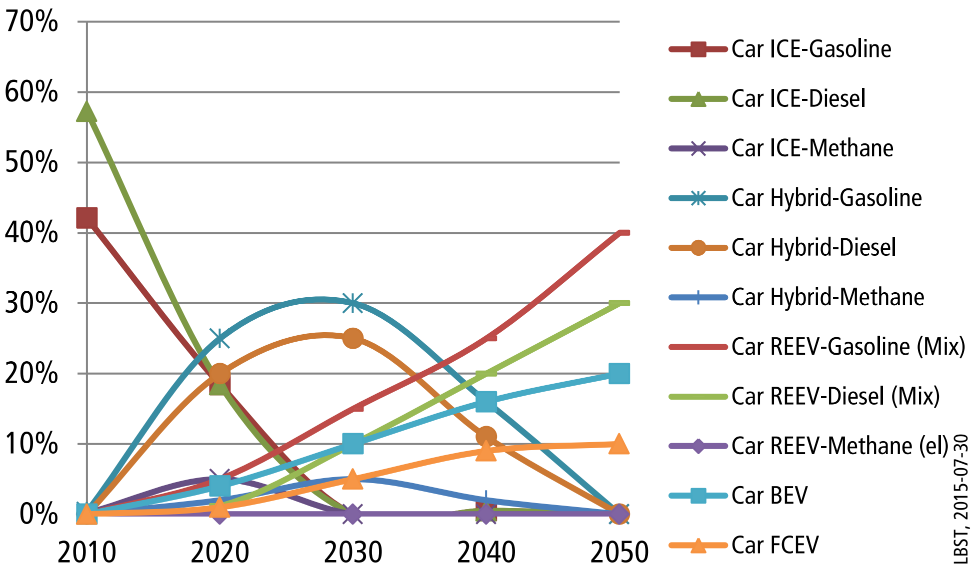


Figure 54: Car deployment «FVV» 2010-2050 in % of new registrations

Table 66: Truck mix of new registrations in the «FVV» scenario

TRUCK [%]	Truck <3.5t			Truck 3.5-12t			Truck/Trailer>12t		
	Diesel	BEV	FCEV	Diesel	Methane	FCEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	92	5	3	90	8	2	95	4	1
2030	60	25	15	65	30	5	78	20	2
2040	20	45	35	30	55	15	48	45	7
2050	5	50	45	10	70	20	30	60	10

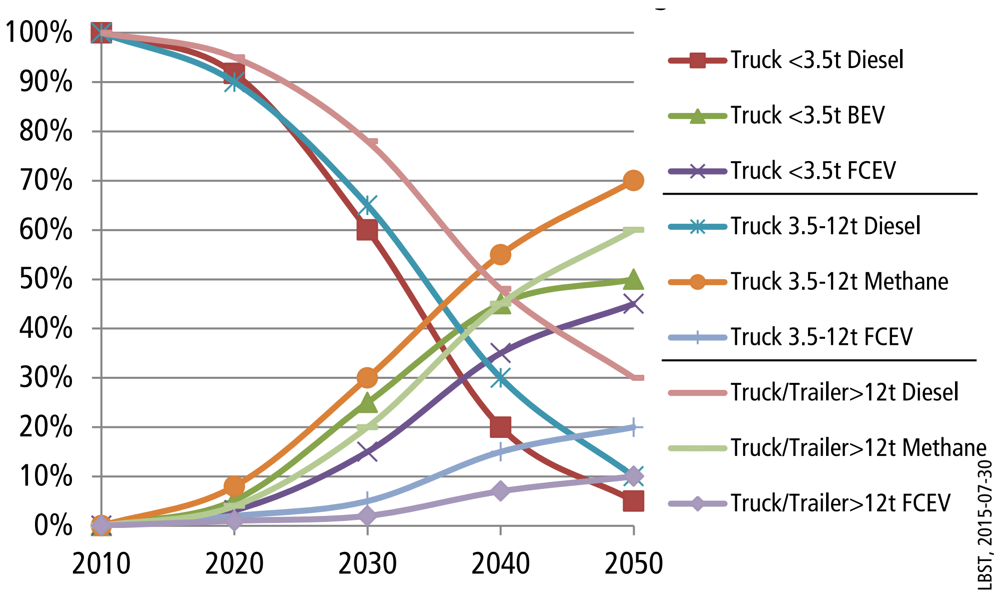


Figure 55: Truck deployment «FVV» 2010-2050 in % of new registrations

Table 67: Bus mix of new registrations in the «FVV» scenario

BUS [%]	ICE Diesel	ICE Methane	FCEV
2010	99	1	0
2020	87	10	3
2030	55	30	15
2040	25	40	35
2050	10	30	60

Table 68: Train mix of new registrations in the «FVV» scenario

TRAIN [%]	Passenger			Freight		
	Electricity (OHL)	Diesel	H_2	Electricity (OHL)	Diesel	H_2
2010	80	20	0	80	20	0
2020	80	18	2	80	15	5
2030	80	16	4	80	9	11
2040	80	14	6	80	7	13
2050	80	12	8	80	5	15

Table 69: Ship mix of new registrations in the «FVV» scenario

SHIP [%]	Inland waterway			Maritime		
	Diesel	Methane	Methanol	Diesel	Methane	Methanol
2010	100	0	0	100	0	0
2020	90	10	0	94	5	1
2030	70	30	0	75	20	5
2040	30	70	0	45	45	10
2050	5	95	0	10	70	20

Table 70: Plane mix of new registrations in the «FVV» scenario

PLANE [%]	Kerosine	LH_2-FC
2010	100	0
2020	100	0
2030	99	1
2040	96	4
2050	90	10

6.3 «eMob» scenario

This fuel/powertrain scenario has been derived from the study ‘eMobil 2050’ [Hacker et al 2014]. The notion behind the eMobil study is to avoid transportation (sufficiency), shift between transportation modes (modal split), and go as electric throughout all transportation modes as possible from a today’s perspective. The eMob scenario thus e.g. comprises battery-electric vehicles, fuel cell-electric vehicles, and novel aircraft propulsion technologies like fuel cells to a greater extent.

Table 71: Car mix of new registrations in the «eMob» scenario

CAR [%]	ICE Gasol./ Diesel	ICE Methane	Hybrid Gasol./ Diesel	Hybrid Methane	REEV Gasol./ Diesel	REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	86	5	3	0	3	0	3	0
2030	68	5	6	0	9	0	12	0
2040	0	0	10	0	17	0	72	0
2050	0	0	5	0	12	0	82	0

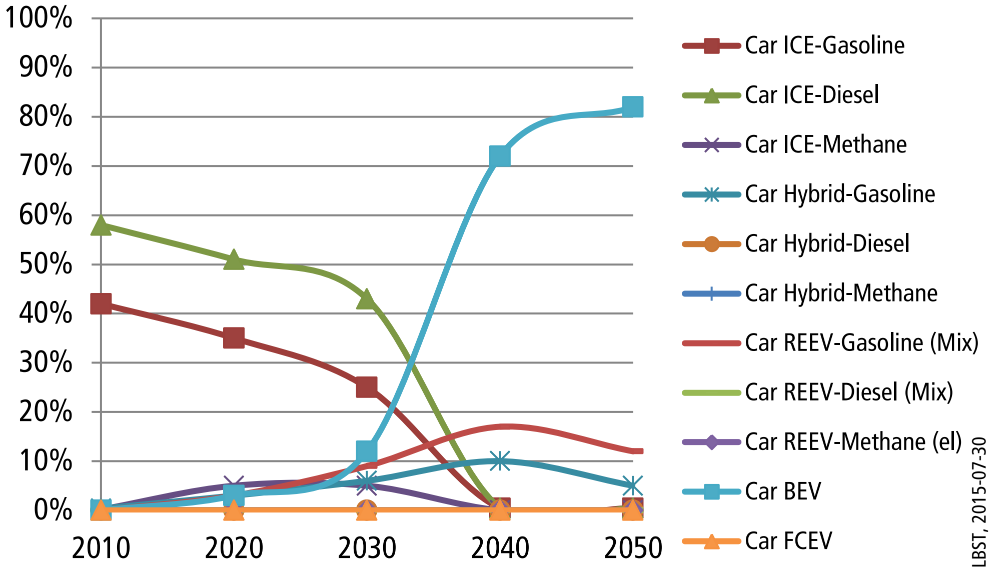


Figure 56: Car deployment «eMob» 2010-2050 in % of new registrations

Table 72: Truck mix of new registrations in the «eMob» scenario

TRUCK [%]	Truck <3.5t			Truck 3.5-12t			Truck/Trailer>12t		
	Diesel	BEV	FCEV	Diesel	Methane	FCEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	96	4	0	96	0	0	100	0	0
2030	75	25	0	75	0	25	85	15	0
2040	10	90	0	10	0	90	55	45	0
2050	10	90	0	10	0	90	53	48	0

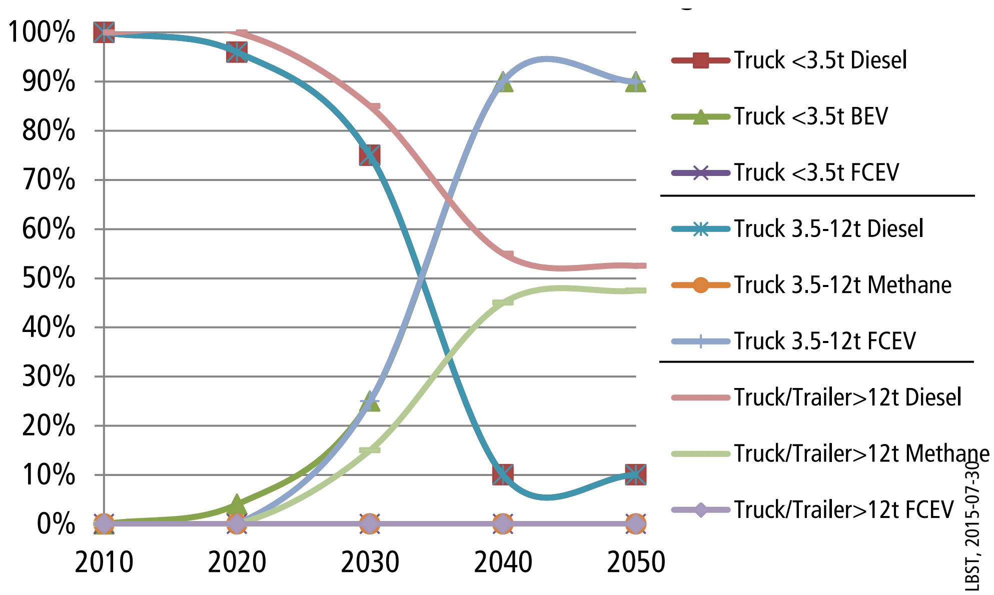


Figure 57: **Truck deployment «eMob» 2010-2050 in % of new registrations**

With regard to buses, some simplifications had to be made in the eMob scenario in order to reduce complexity and be technology-wise in line with the other scenarios. The eMobil 2050 study differentiates between buses for line-service and journey-service. For the purpose of this study, the two categories have not been differentiated here. Furthermore, the eMobil 2050 'Regional' study considers plug-in hybrid buses as an additional fuel/powertrain category which we have added to the 'ICE Diesel' buses here. Finally, eMobil 2050 assumes BEV buses for urban service while here FCEV buses are assumed as a versatile option for a broad range of bus applications; this results in a slightly more conservative estimation of electricity demands from electric buses. All in all, the fuel demand of 135 TWh/a from all buses is relatively low compared to all fuel demands of 2752 TWh/a from road transportation in 2050 (~5%).

Table 73: **Bus mix of new registrations in the «eMob» scenario**

BUS [%]	ICE Diesel	ICE Methane	FCEV
2010	99	1	0
2020	97	3	1
2030	75	10	15
2040	25	25	50
2050	20	30	50

For trains, the study eMobil 2050 provides only specific vehicle consumptions, no fleet data. For this study it is thus assumed that Diesel reductions are replaced by hydrogen powered trains.

Table 74: Train mix of new registrations in the «eMob» scenario

TRAIN [%]	Passenger			Freight		
	Electricity (OHL)	Diesel	H_2	Electricity (OHL)	Diesel	H_2
2010	80	20	0	80	20	0
2020	80	15	5	80	15	5
2030	80	10	10	80	10	10
2040	80	5	15	80	5	15
2050	80	1	19	80	1	19

Maritime shipping has not been detailed in the eMobil 2050 study, thus the same assumptions were taken as per inland waterway navigation.

Table 75: Ship mix of new registrations in the «eMob» scenario

SHIP [%]	Inland waterway			Maritime		
	Diesel	Methane	Methanol	Diesel	Methane	Methanol
2010	100	0	0	100	0	0
2020	100	0	0	100	0	0
2030	100	0	0	100	0	0
2040	100	0	0	100	0	0
2050	100	0	0	100	0	0

Aviation has not been detailed in the eMobil 2050 study, thus we have assumed that in a world where everything tends to be more or even all-electric also the planes with have higher shares of electric mobility. Furthermore, electric propulsion reduces the climate impact from high-altitude combustion emissions, which also fits into the notion of the eMob scenario.

Table 76: **Plane mix of new registrations in the «eMob» scenario**

PLANE [%]	Kerosene	LH_2-FC
2010	100	0
2020	99	1
2030	92	8
2040	75	25
2050	65	35

6.4 Comparison

In the transportation model, the shares of newly registered vehicles as per scenario definitions in chapters 6.1 through 6.3 are calculated to cover the HIGH and LOW transportation demands as defined in chapter 4. For a better understanding of the fuel/powertrain distribution in the various scenario combinations, Figure 58 and Figure 59 give a 2050 overview over the percentage-contributions of fuel/powertrains to supply the person-km and tonne-km in both the HIGH and in the LOW transportation demand case for Germany and the EU-28 respectively.

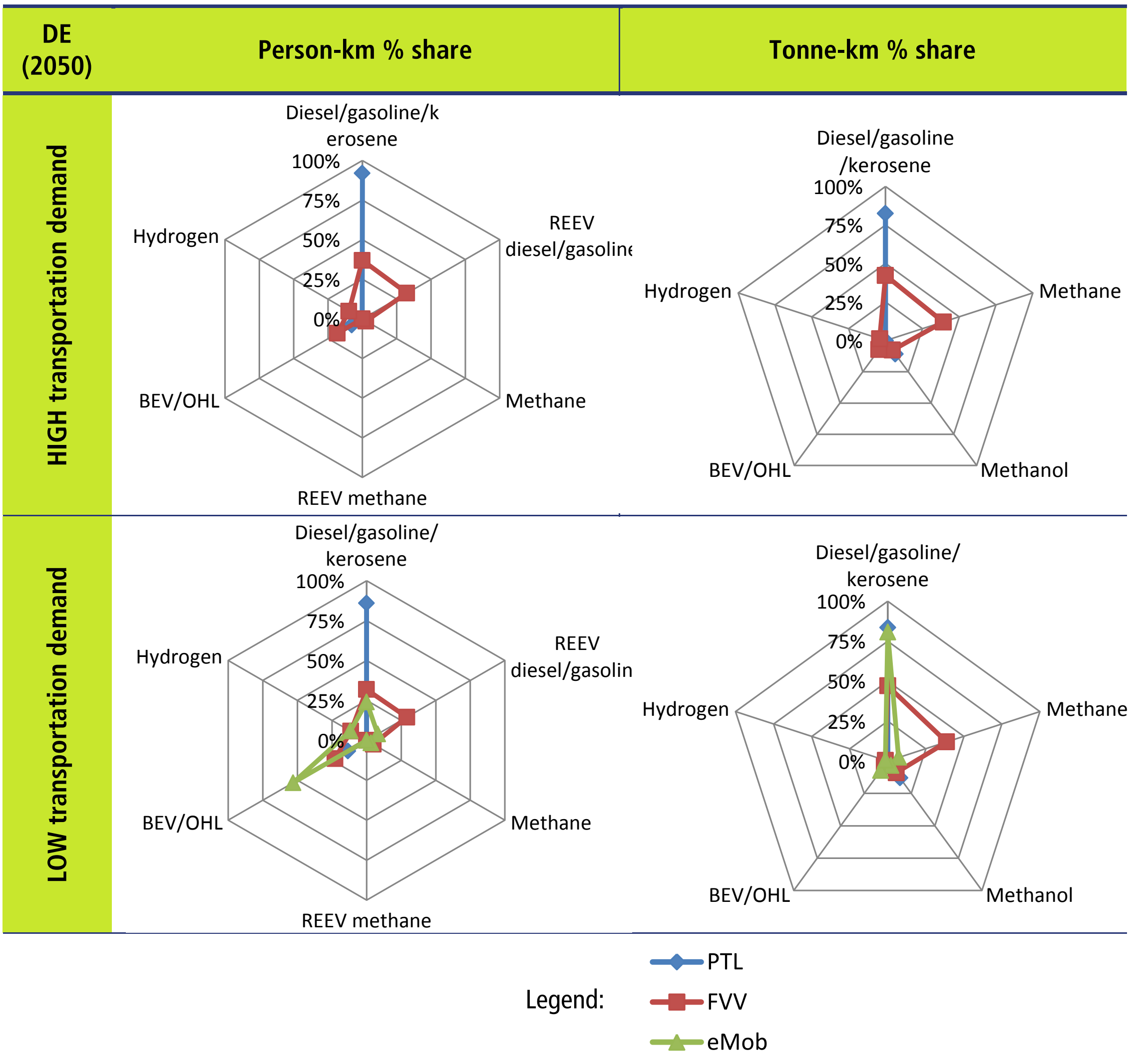


Figure 58: Percentage shares of fuel/powertrains to supply person-km and transport-km demands in Germany in 2050

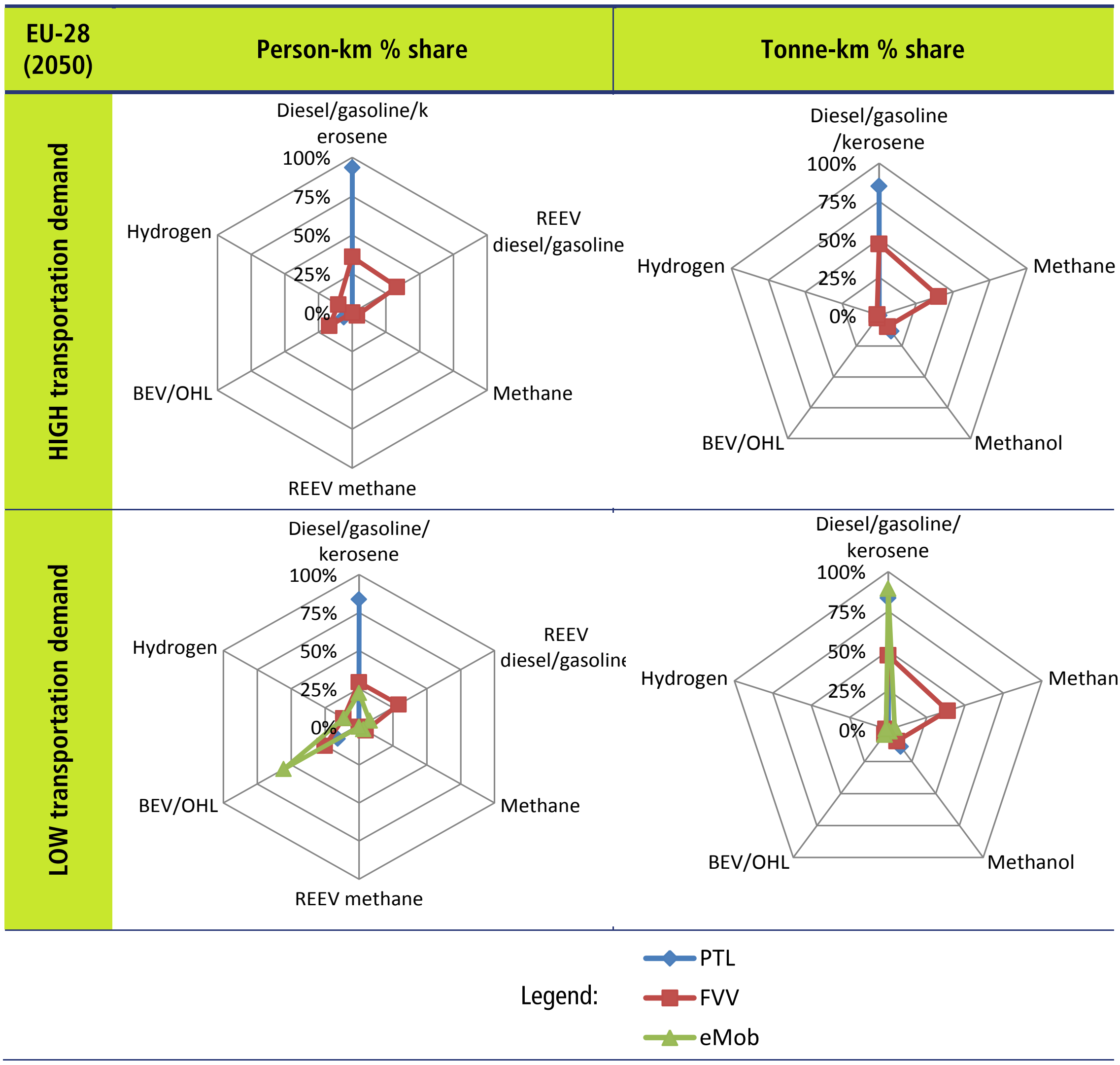


Figure 59: **Percentage shares of fuel/powertrains to supply person-km and transport-km demands in EU-28 in 2050**

Note that the eMob fuel/powertrain scenario has not been crossed with the HIGH transportation demand scenario for consistency reasons. Both the eMob and the HIGH scenario represent completely different 'future worlds'.

From Figure 58 and Figure 59 it can be seen that in spite of the differences between EU-28 and the German transportation sector structure and developments, the percentage shares are quite comparable to each other. The values of course differ significantly in absolute terms between the two geographies.

Time-rows for electricity and fuel consumption as well as the corresponding renewable electricity demands are depicted in the following results chapter 7.

7 RESULTING ENERGY DEMAND, GREENHOUSE GAS EMISSIONS AND CUMULATED INVESTMENTS

In this chapter, the resulting fuel and electricity demands, greenhouse gas emissions and cumulated investments until 2050 are compiled.

7.1 Scenario fuel demands

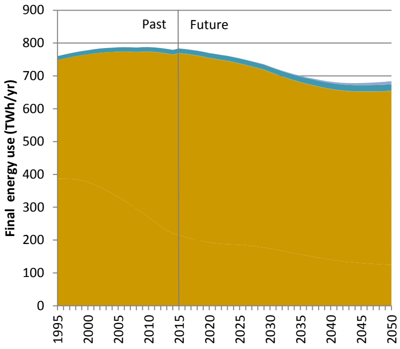
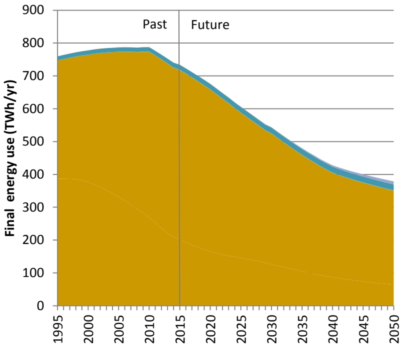
From the scenarios and assumptions as described in chapters 4, 5, and 6, the following fuel demands result for Germany and the EU-28.

From the results it can be concluded that transportation fuel demands decrease in all scenarios because of the improvements in propulsion efficiency assumed. The primary energy demands, i.e. the renewable electricity consumed for transportation, however increase because of the energy efforts needed to produce the final PtX fuels (PtH_2, PtCH_4, PtL, electricity for BEV charging, electricity for overhead lines).

a) Germany

In Table 77, the final energy demand in scenarios for Germany is depicted by type of fuel.

Table 77: Scenarios’ fuel demands for Germany (depicted by fuel)

<table>
<tr><th>DE
[TWh]</th><th>HIGH transportation demand</th><th>LOW transportation demand</th></tr>
<tr><td>«PTL»</td><td>
</td><td>
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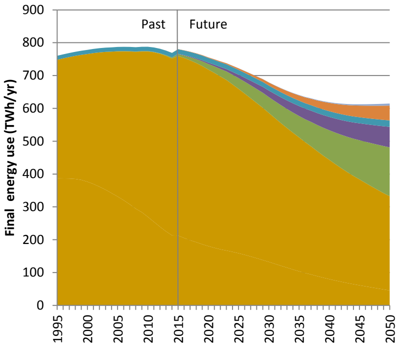
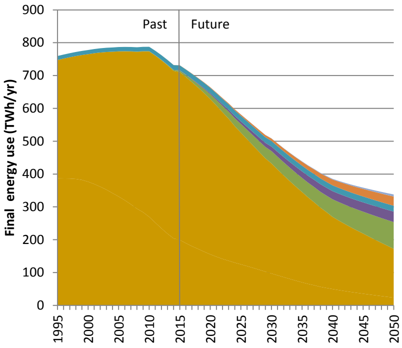
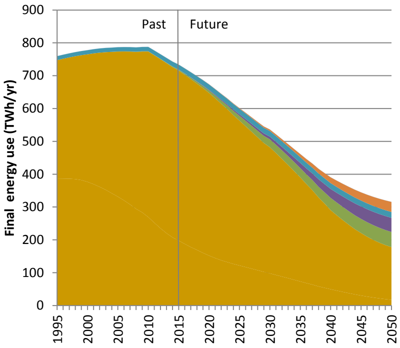
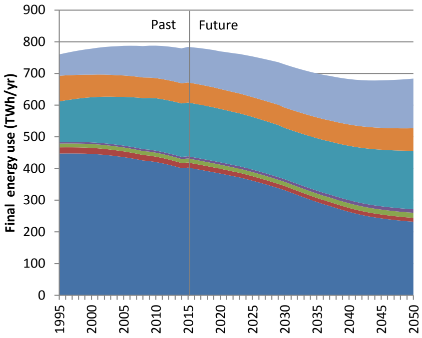
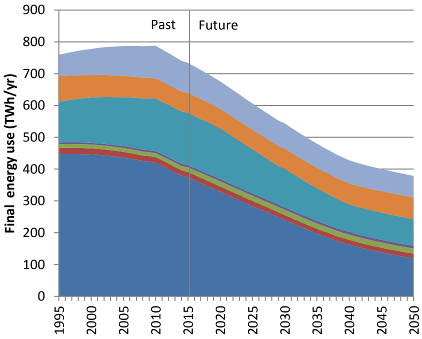
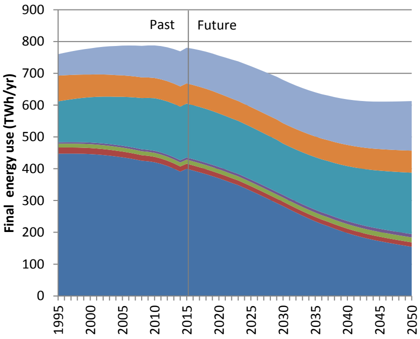
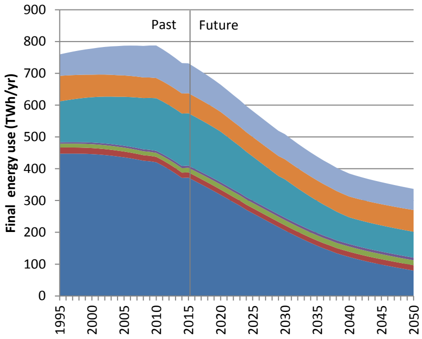
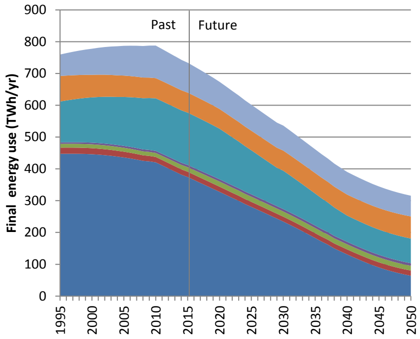
<tr><td>«FVV»</td><td>
</td><td>
</td></tr>
<tr><td>«eMob»</td><td>Legend:
🟦 Methanol
🟧 H2
🟦 Electricity (train)
🟪 Electricity (0.4 kV)
🟩 Methane
🟨 Diesel/Kerosene
🟨 Gasoline</td><td>
</td></tr>
</table>

The dominance of power-to-liquids (PtL diesel and PtL gasoline) in Table 77 for Germany and Table 79 for EU-28 also in the electric mobility (eMob) and the FVV+LOW scenarios is mainly determined by two factors:

- Freight transport requires a relatively high share of all transportation fuel demands, and high-performance truck and shipping have been assumed to run predominantly with internal combustion engines.
- Fuel demands from battery- and fuel cell-electric powertrains are lower compared to propulsion systems comprising internal combustion engines.

In Table 78, the final energy demands in Germany are depicted by transportation mode.

Table 78: Scenarios' fuel demands for Germany (depicted by mode)

DE [TWh]	HIGH transportation demand	LOW transportation demand
«PTL»		
«FVV»		
«eMob»	Legend: ■ Aviation ■ Ships (freight) ■ Trucks ■ Rail (freight) ■ Rail (passenger) ■ Buses ■ Passenger vehicles	

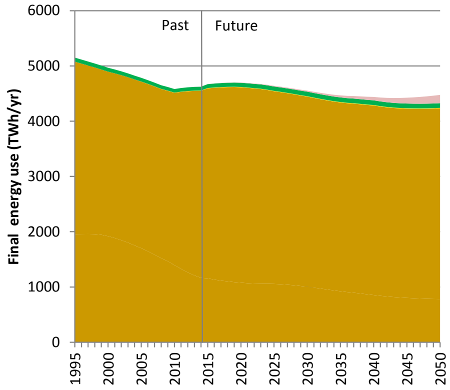
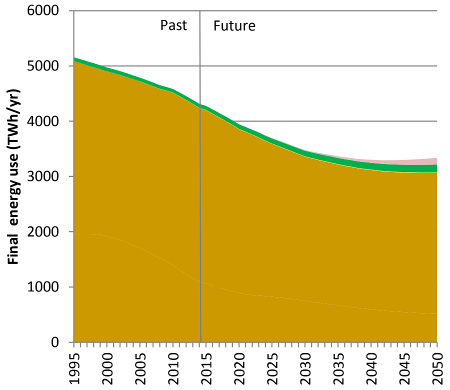
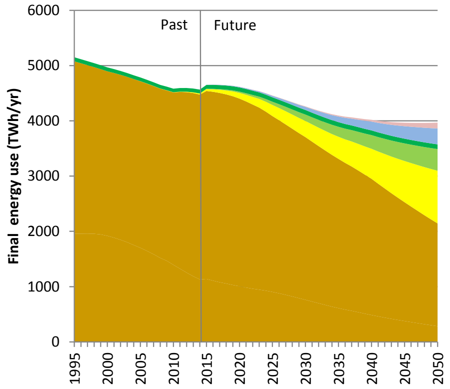
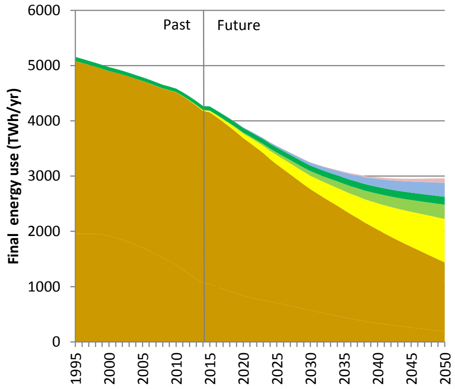
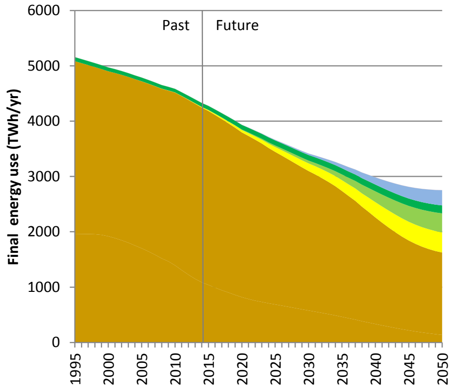
From Table 78 it can be seen that the relative importance of trucks and aviation in fuel demand increases. Aviation fuel demand goes predominantly into international relations. International shipping has not been modelled in the German case as other cargo harbours outside Germany (notably Rotterdam) play an important role in German international cargo shipping, too. International shipping has been considered in the European model run, see the following chapter below.

For comparison, the German transportation fuel demand was some 730 TWh in 2014.

b) Europe

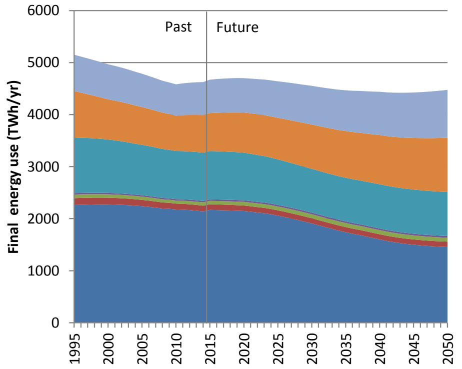
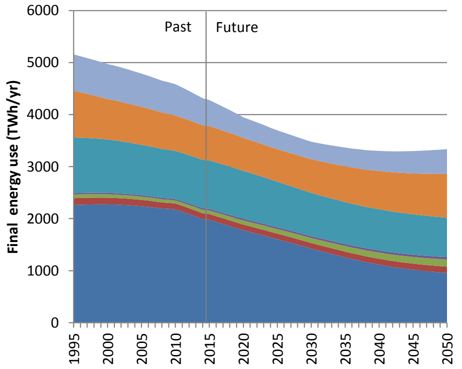
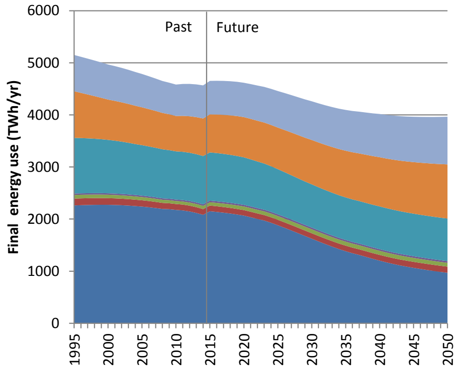
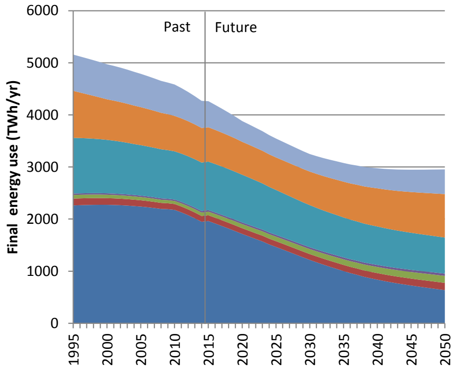
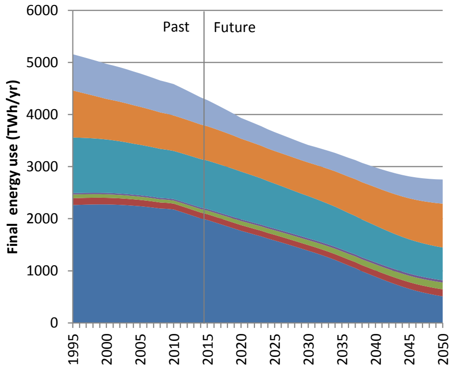
In Table 79, the final energy demand in scenarios for EU-28 is depicted by type of fuel.

Table 79: **Scenarios' fuel demands for EU-28 (depicted by fuel)**

<table>
<tr><th>EU-28 [TWh]</th><th>HIGH transportation demand</th><th>LOW transportation demand</th></tr>
<tr><td>«PTL»</td><td>
</td><td>
</td></tr>
<tr><td>«FVV»</td><td>
</td><td>
</td></tr>
<tr><td>«eMob»</td><td>Legend:
■ Methanol
■ H2
■ Electricity (train)
■ Electricity (0.4 kV)
■ Methane
■ Diesel/Kerosene
■ Gasoline</td><td>
</td></tr>
</table>

In Table 80, the final energy demand in scenarios for EU-28 is depicted by transport mode.

Table 80: Scenarios' fuel demands for EU-28 (depicted by mode)

EU-28 [TWh]	HIGH transportation demand	LOW transportation demand
«PTL»		
«FVV»		
«eMob»	Legend: ■ Aviation ■ Ships (freight) ■ Trucks ■ Rail (freight) ■ Rail (passenger) ■ Buses ■ Passenger vehicles	

From Table 80 it can be seen that the relative importance of trucks, ships, and aviation increases. With regard to the ship and aviation sector, the fuels are predominantly consumed in international relations.

For comparison, the EU transport fuel demand (heating value) was ~4600 TWh in 2013.

7.2 Scenario electricity demands

Figure 60 and Figure 61 compare the German and EU-28 transportation electricity demands from different scenarios. Transportation electricity demands are shown on top of today's electricity demand. Today's electricity demand is kept constant because a discussion of new electricity consumers – like power-to-heat, power-to-chemicals, etc. – versus electricity demand reductions induced by energy efficiency targets would merit a modelling study of its own.

a) Germany

Figure 60 compares the German transportation electricity demands from different combinations of fuel/powertrain and transportation demand scenarios.

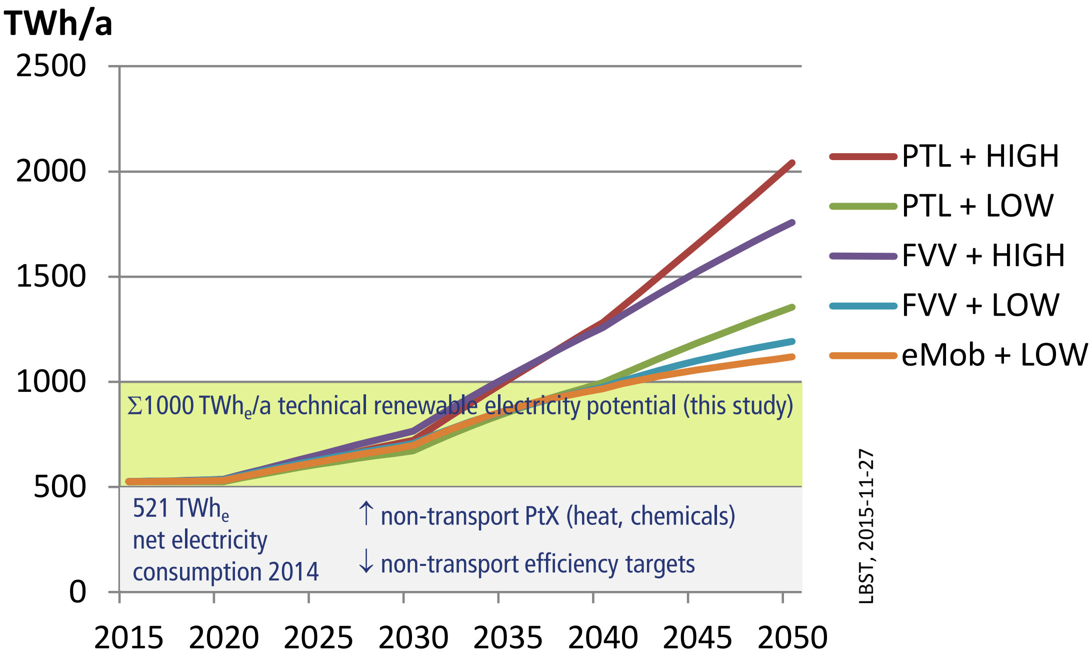


Figure 60: Renewable electricity demand from the transport sector versus technical renewable electricity potential for Germany

To put the electricity demands from German scenarios into perspective, the net electricity demand (all sectors and uses) was 521 TWh$_e$ in 2014. All German scenarios would likely require renewable energy imports.

For the supply of transportation electricity demands, an equivalent of 360-900 GW installed renewable power capacities is required by 2050. For comparison, in 2014 about 80 GW of installed renewable power plant capacities (thereof 38 GW wind onshore, 3 GW wind offshore, 39 GW photovoltaics) were covering some 25% of the total electricity consumption in Germany.

b) Europe

Figure 61 compares the EU-28 transportation electricity demands from different scenarios.

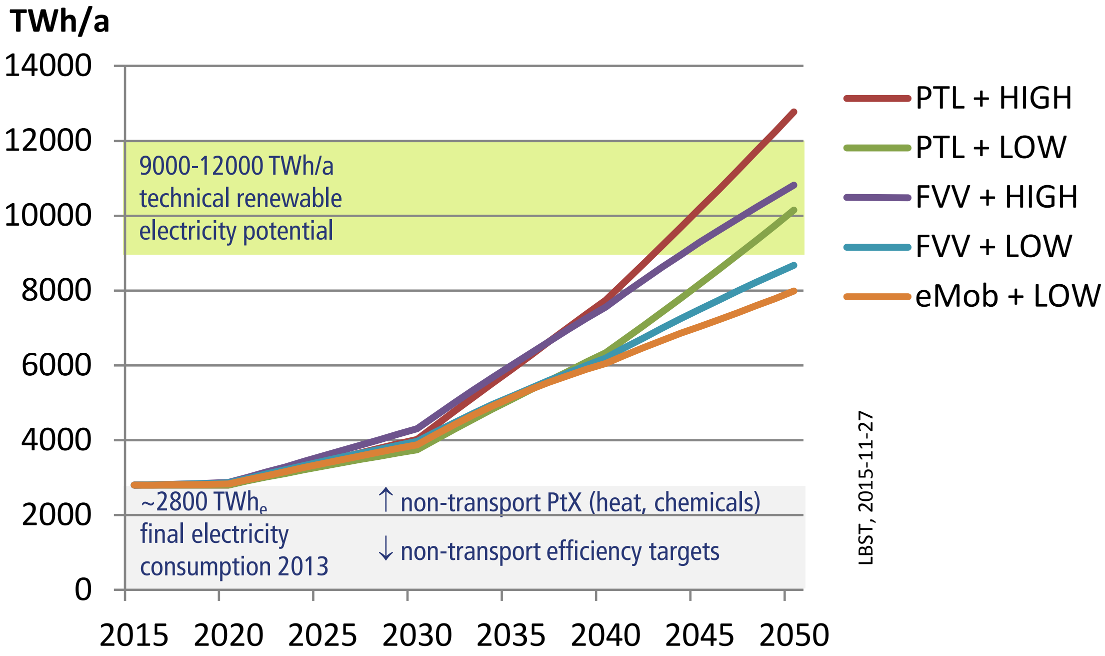


Figure 61: **Renewable electricity demand from the transport sector versus technical renewable electricity potential for EU-28**

From Figure 61 can be concluded that all EU scenarios but PTL+HIGH might be feasible using domestic renewable electricity production.

To put the scenario electricity demands into perspective, the EU net electricity demand from all sectors/uses was some 2800 TWh$_e$ in 2013. Considering scenario electricity demands as depicted in Figure 61, it becomes clear that the total electricity demand in 2050 could easily reach a factor 3 to 4.5 of today's total electricity demands in the EU-28.

For the supply of transportation electricity demands, an equivalent of 2200-4300 GW installed renewable power capacities are required by 2050. For comparison, in 2014 just over 364 GW of installed renewable power plant capacities where in place, thereof 150 GW hydro, 121 GW wind onshore, 8 GW wind offshore, and 85 GW photovoltaics.

For both, **Germany and EU-28 scenario results**, it can be concluded that the transportation demand is the key driver for energy use across all scenarios. Truck freight and aviation are the key drivers that push transportation demand in the HIGH scenarios.

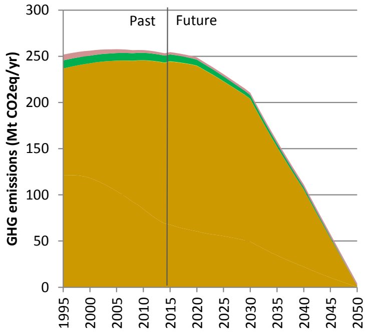
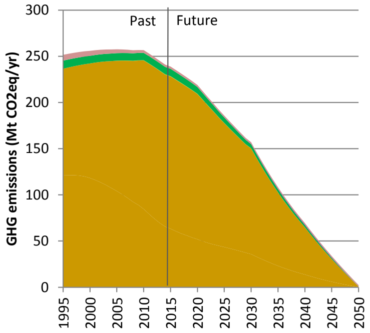
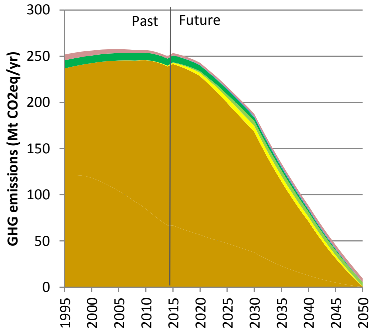
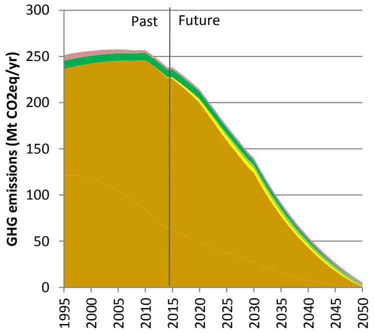
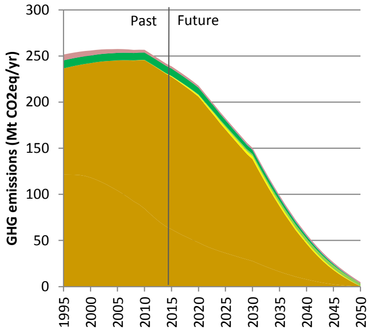
7.3 Scenario greenhouse gas emissions

Greenhouse gas emission reductions are due to the energy transition in the primary energy base, i.e. the target scenario to achieve 100% renewable electricity and electricity-based PtX fuels by 2050. Greenhouse gas emissions have been calculated 'well-to-tank' including combustion of the carbon bound in $PtCH_4$ and PtL. Note that climate impacts from high-altitude emissions of aviation are not included in the following figures.

a) Germany

In Table 87Table 77, greenhouse gas emissions are depicted by type of fuel for German scenarios.

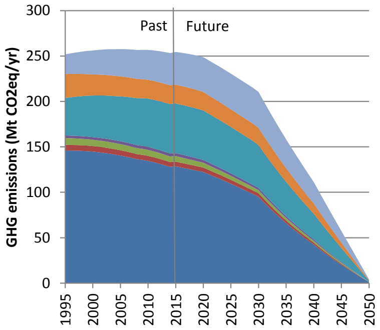
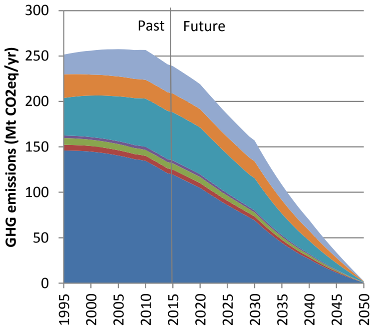
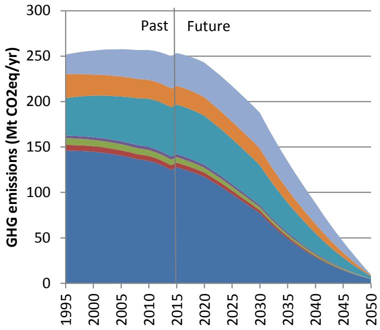
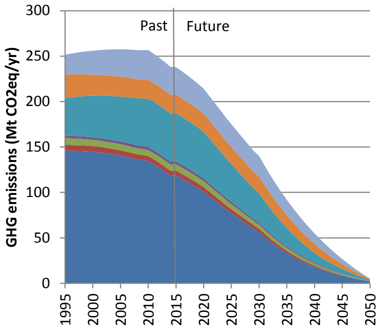
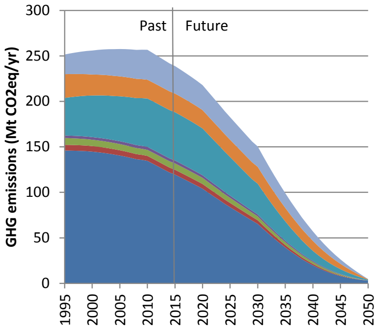
Table 81: Scenarios' GHG emissions for Germany (depicted by fuel)

DE [TWh]	HIGH transportation demand	LOW transportation demand
«PTL»		
«FVV»		
«eMob»	Legend: 🟥 Non-CO2-GHG vehicle 🟪 Methanol 🟦 H2 🟩 Electricity mix (train) 🟩 Electricity mix (0.4 kV) 🟨 CH4 🟧 Diesel/Kerosene 🟧 Gasoline	

Note: Climate impacts from high-altitude emissions of aviation are not included.

In Table 88, the greenhouse gas emissions are depicted by transportation mode for German scenarios.

Table 82: Scenarios' GHG emissions for Germany (depicted by mode)

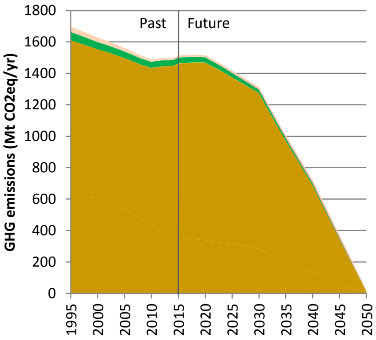
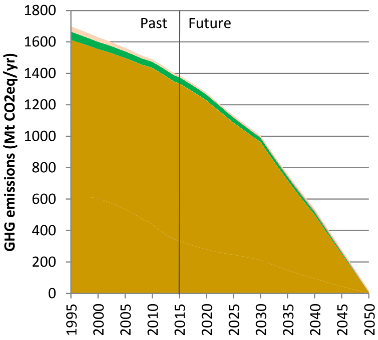
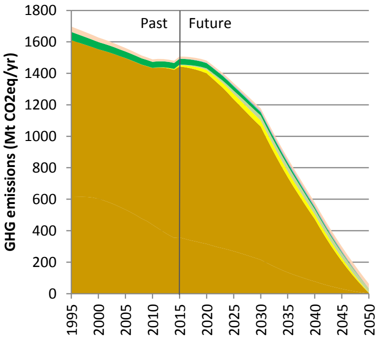
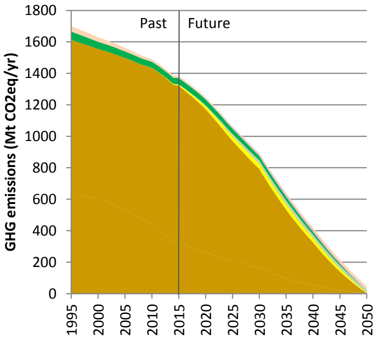
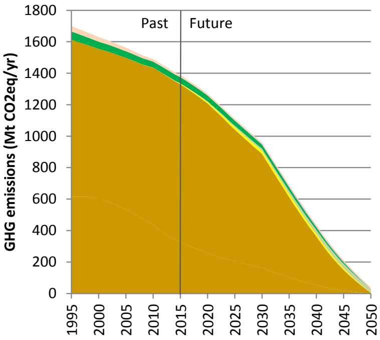
DE [TWh]	**HIGH transportation demand**	**LOW transportation demand**
«PTL»		
«FVV»		
«eMob»	Legend: 🟦 Aviation 🟧 Ships (freight) 🟦 Trucks 🟪 Rail (freight) 🟩 Rail (passenger) 🟥 Buses 🟦 Passenger vehicles	

Note: Climate impacts from high-altitude emissions of aviation are not included.

b) Europe

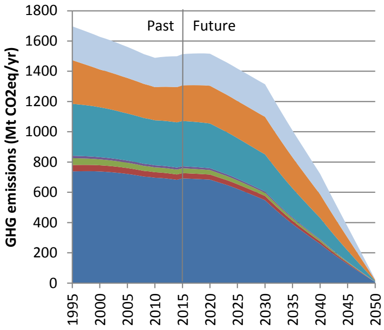
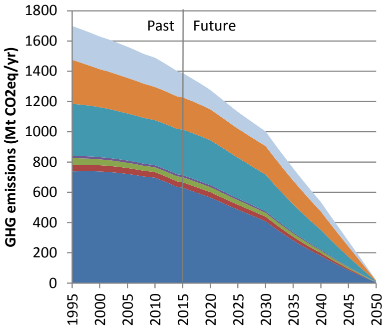
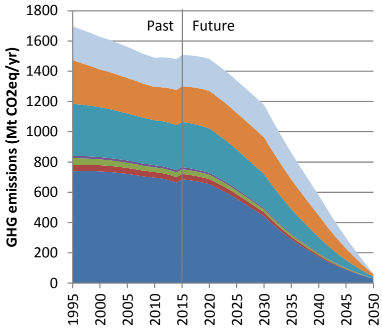
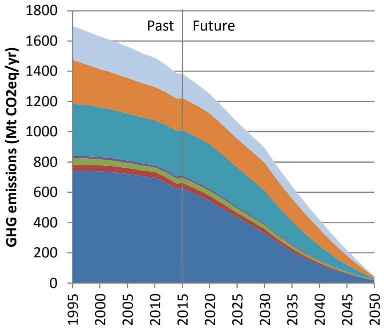
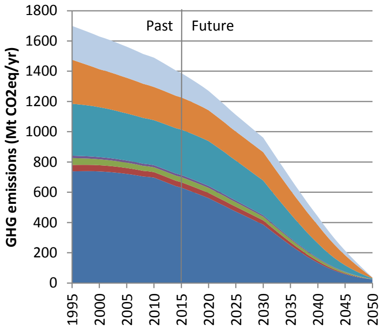
In Table 89Table 77, the greenhouse gas emissions are depicted by type of fuel for EU scenarios.

Table 83: Scenarios' GHG emissions for EU-28 (depicted by fuel)

EU-28 [TWh]	**HIGH transportation demand**	**LOW transportation demand**
«PTL»		
«FVV»		
«eMob»	Legend: ■ Non-CO2-GHG vehicle ■ Methanol ■ H2 ■ Electricity mix (train) ■ Electricity mix (0.4 kV) ■ CH4 ■ Diesel/Kerosene ■ Gasoline	

In Table 84, the greenhouse gas emissions are depicted by transportation mode for EU scenarios.

Table 84: Scenarios’ GHG emissions for EU-28 (depicted by mode)

EU-28 [TWh]	HIGH transportation demand	LOW transportation demand
«PTL»		
«FVV»		
«eMob»	Legend: ■ Aviation ■ Ships (freight) ■ Trucks ■ Rail (freight) ■ Rail (passenger) ■ Buses ■ Passenger vehicles	

7.4 Scenario cumulated investment until 2050

All investments that are required for a transportation energy transition to 100% renewable electricity/PtX fuels 2050 have been cumulated. The cumulated investments comprise the following investment positions:

- Renewable power plants (wind onshore, wind offshore, PV, concentrated solar power)
- Power-to-X production plants (hydrogen production, syntheses processes, upgrading)
- Distribution infrastructure (gasoline/kerosene/diesel, methane, and hydrogen stations[7])

Investments take technology learning curves into account, i.e. the 1st plant is more expensive than the nth one. For details regarding fuel specific assumptions, refer to chapter 5.1. For time-series on cumulated investments for PtX plants, refer to Annex A4.

a) Germany

Figure 62 shows the cumulated investments for Germany for the renewable transportation fuel scenarios assessed in this study.

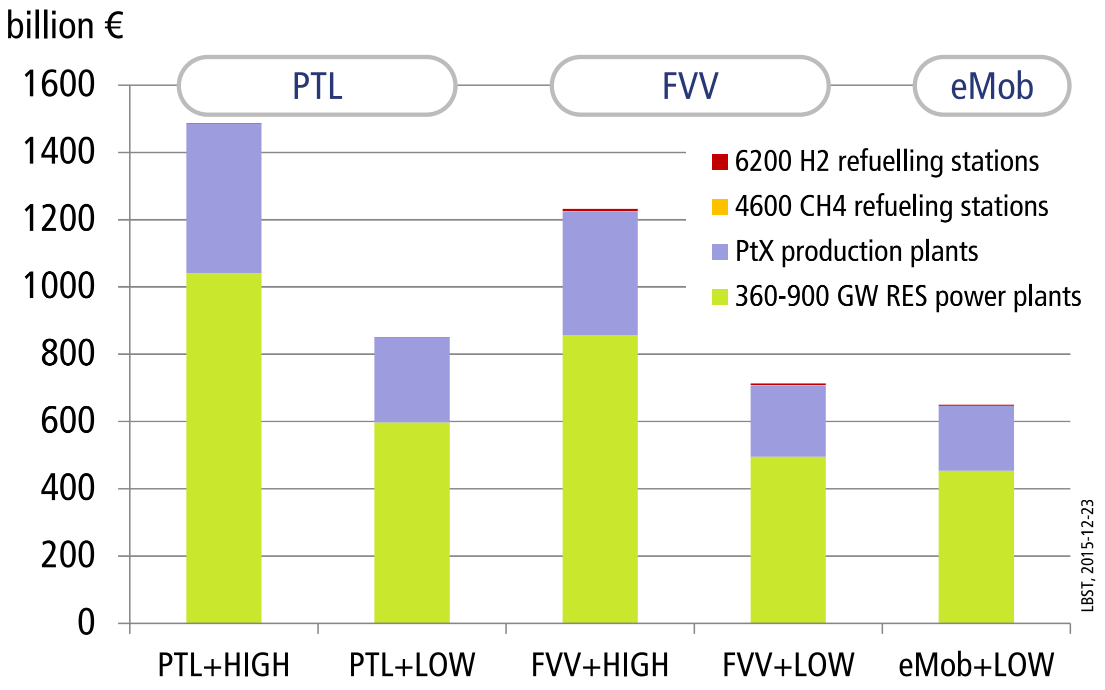


Figure 62: **Cumulated investments until 2050 incurred in Germany scenarios, depicted by cost item**

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[7] In case of hydrogen the hydrogen is generated onsite the refuelling station. Therefore, no further infrastructure is required

Depending on the scenario, the total cumulated investments required for renewable power plants, PtX plants, and fuel distribution infrastructure are between 650 (eMob + LOW) and 1490 billion € (PTL + HIGH). Cumulated investment for PtX plants alone range between 190 and 440 billion €, respectively.

For comparison, in Germany, the gross domestic product (GDP) amounted to about 2900 billion € in 2014. The linear average of cumulated investments over 35 years results in average investment needs of 18.6 and 41.4 billion € per year. That is the equivalent to about 0.6 to 1.4% of the GDP in Germany, respectively.

Investments may also be compared with investments for vehicles in Germany. According to [Uni Duisburg 2015] the average price for a passenger car amounts to about 28,000 €. The average vehicle sales amount to about 3 million per year. Assuming the average vehicles sales and the average vehicle price to be constant in the next 35 years leads to an annual investment of 84 billion € per year or about 2940 billion € until 2050 for vehicles, i.e. 2 to 4.5 times the investments for renewable fuel production and distribution.

b) Europe

Figure 63 shows the cumulated investments for the EU-28 renewable transportation fuel scenarios assessed in this study.

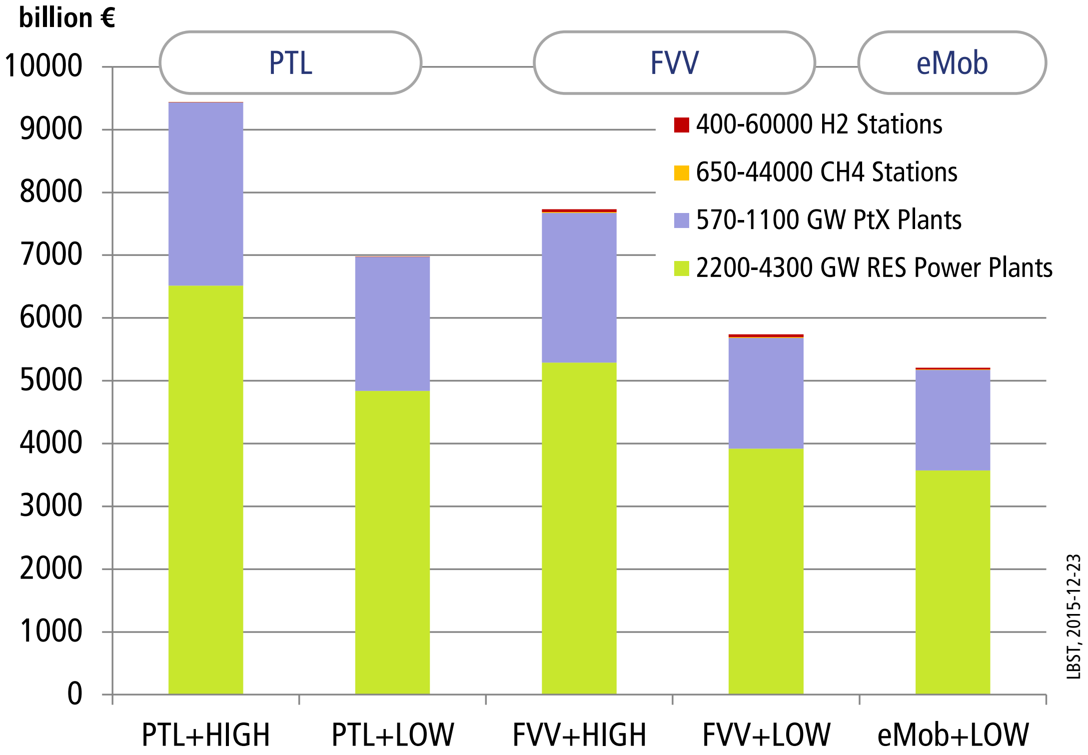

Figure 63: **Cumulated investments until 2050 incurred in EU-28 scenarios, depicted by cost item**

Depending on the scenario, the total cumulated investments required for renewable power plants, PtX plants, and fuel distribution infrastructure are between 5206 (eMob+LOW) and 9435 billion € (PTL+HIGH).

The investment for infrastructure as well as for methane and hydrogen is low even for scenarios where 60,000 hydrogen refueling stations are installed. For example, if a hydrogen refueling station costs 1 million € and 60,000 refuelling stations were built in the EU the investment would be about 60 billion € or about 1% of the total investment for scenario FVV+LOW only.

The lower limit (e.g. 400 hydrogen refuelling stations) represents a scenario where the amount of hydrogen dispensed is very low and hydrogen is only used in a few regions of the EU. For the introduction of hydrogen in a region a minimum number of refueling stations is required. The minimum number of methane and hydrogen refueling stations is assumed to be 400 (which is the number of refueling stations planned by H2Mobility until 2023 in Germany). Higher methane or hydrogen demand leads to an increase of the number of refueling stations.

For comparison, the EU gross domestic product (GDP) amounted to about 13920 billion € in 2014. The linear average of cumulated investments over 35 years results in average investment needs of 150 and 267 billion € per year. That is the equivalent to about 1 to 1.9% of the GDP in Europe, respectively.

For comparison, the EU fossil oil spendings were about 290 billion € in 2014. In fact, this is about the same level or even significantly more than what was needed for an energy transition to 100% renewable transportation fuels in Europe by 2050.

7.5 Overview of scenario results

The following Figure 64 and Figure 65 provide a condensed overview over the scenario results for Germany and Europe respectively.

	HIGH transportation demand	LOW transportation demand
PTL	Fuel demand: 680 TWh/a Electricity demand PtX: 1520 TWh/a Cumulated investments: € 1490 billion	Fuel demand: 380 TWh/a Electricity demand PtX: 830 TWh/a Cumulated investments: € 850 billion
FVV	Fuel demand: 610 TWh/a Electricity demand PtX: 1190 TWh/a Cumulated investments: € 1230 billion	Fuel demand: 340 TWh/a Electricity demand PtX: 640 TWh/a Cumulated investments: € 710 billion
eMob		Fuel demand: 320 TWh/a Electricity demand PtX: 590 TWh/a Cumulated investments: € 650 billion

Figure 64: German scenario results in a nutshell

	HIGH transportation demand	LOW transportation demand
PTL	Fuel demand: 4480 TWh/a Total electricity demand: 9990 TWh/a Cumulated investments: € 9440 billion	Fuel demand: 3340 TWh/a Total electricity demand: 7370 TWh/a Cumulated investments: € 6980 billion
FVV	Fuel demand: 3970 TWh/a Total electricity demand: 7720 TWh/a Cumulated investments: € 7730 billion	Fuel demand: 2960 TWh/a Total electricity demand: 5640 TWh/a Cumulated investments: € 5740 billion
eMob		Fuel demand: 2750 TWh/a Total electricity demand: 5130 TWh/a Cumulated investments: € 5210 billion

Figure 65: EU-28 scenario results in a nutshell

8 CONCLUSIONS & RECOMMENDATIONS

In order to fulfil German and EU climate targets of -80 to -95% greenhouse gas emissions from all sectors, the transportation sector will have to become practically emissions free by 2050, especially in case of further growth in transportation demands.

To achieve this, there are a heap of options:

- Propulsion efficiency (MJ/km)
- Change in transportation demand (Pkm, tkm)
- Change in modal split
- Renewable transport fuels

Increasing transportation demands are to be counterbalanced with increasing greenhouse gas mitigation efforts per unit of transportation. Increasing the propulsion efficiency is important, but will not be sufficient alone. Medium to long-term greenhouse gas reductions will require the use of renewable fuels, or avoidance. In this study, a target scenario to 100% renewable fuels by 2050 was assumed to understand the implications resulting from a set of distinctly different transportation demand and vehicle mix scenarios.

Fuels and drives

There are two drivers that directly determine the specific energy demands from transport (well-to-use), that is the vehicle consumption (tank-to-use) and the energy efforts for fuel production and distribution (well-to-tank). From a scenario point of view, the optimal fuel is the fuel not needed.

Powertrain options that give significant and robust energy efficiency improvements are:

- Increase of powertrain efficiency, notably via hybridisation, and electric vehicles with combustion engines, e.g. as range extender (REEV)
- Fuel cell (FCEV) and battery electric vehicle (BEV)

Fuels with low energy demands for their production, such as electricity or hydrogen, require dedicated infrastructures and novel propulsion systems. Both electricity for battery-electric vehicles and for hydrogen, methane, and liquid hydrocarbons can be produced from renewable power. The direct use of renewable power in transport is most energy-efficient, however, additional stationary electricity storage capacities may be needed, especially with (ultra) fast charging or catenary lines. Power-to-gases (PtH_2, $PtCH_4$) require less energy input than power-to-liquids (PtL). The use of high-temperature electrolysis in combination with waste heat from synthesis reactions is favourable efficiency-wise; high-temperature routes have to be up-scaled to industrial capacities still.

Scenario energy demand

Depending on the transport-related scenarios and electricity demand developments and electricity demand from non-transport sectors as per today, the total electricity demand in 2050 may be in the range of factor 1.1 to 3 (Germany) and 3 to 4.5 (EU-28) of the total electricity demand today.

In the EU, all scenarios except PTL+HIGH could technically be satisfied with domestic renewable electricity in the EU. In densely populated Germany, all the scenarios analysed exceed the technical or acceptable renewable electricity potentials. PtL is particularly adequate for fuel import due to its high energy densities and potentially lower renewable electricity generation costs in remote places. To cover the electricity demands from transportation, significant amounts of additional renewable power plants have to be built-up at ramp rates between 60-220 GW_e/a (PTL+HIGH) and 50-120 GW_e/a (eMob+LOW) in the case of EU-28. Recent deployment rates of renewable power plants need to be sustained in Germany and deployment stepped-up in the EU-28 throughout the next decades.

Fuel costs

Fuel costs are a significant hurdle to the deployment of renewable fuels. For a level-playing field, their value to the environment and society would have to be reflected in fuel price building. Besides transportation avoidance, there are hardly any sustainable 'no regret' options to reduce greenhouse gas emissions in transportation, especially with regards to achieve mid- to long-term targets. Among the PtX pathways analysed in this study, hydrogen from water electrolysis with renewable electricity has the lowest CO_2 mitigation costs both in the short and in the long-term.

PtX costs are dominated by electricity costs, which strongly depend on the fuel choice (H_2, CH_4, PtL) and associated plant efficiencies. Along with further deployment of renewable power plants, PtX fuel costs could half between 2015 and 2050. PtL imports from preferred geographies could be some 20% lower in costs. In order for PtL to achieve cost parity (excluding taxes) with today's fuel costs (including taxes), renewable electricity costs in the order of 3 ct/kWh_e and 4000 annual equivalent full load hours are required.

While this study has built on full-cost assessments for a comprehensive and fair comparison of long-term development pathways, opportunities for cost reductions also in the short-term may be identified through project-specific assessments applying business case approaches.

If well established, PtX fuel options may all end up in the same cost range. PtL assumptions, especially high-temperature electrolysis, have yet to be proven with installations at commercial scales. In order to achieve PV production costs in the range of 2-3 ct/kWh_e, technology break-troughs and established value chains in countries with high solar irradiation are required [ISE 2015].

Cumulated investments

The annual investment needs for all the scenarios analysed are in average in the order of 0.5 to 2% of current GDP. This range seems manageable considering that it includes all investments for a transition to 100% renewable fuels in transport by 2050: renewable power plants, PtX production plants, and distribution infrastructure (excluding vehicles, which have not been in the study scope).

The level of required annual investments strongly correlates with the transportation demand, then with the fuel/powertrain mix. The more low-energy intensive fuels are used to power a mix of high-efficient propulsion systems, the lower the overall investment needs. Common to all fuel/powertrain scenarios is that the fuel distribution infrastructure has only a marginal (almost negligible) share in total cumulated investments. While this is all true from a macro-economic perspective, from an investor position there are significant challenges in the transition phase though, e.g. for deploying alternative fuel distribution infrastructures with their typical underutilisation in the beginning. A lack of early and sufficient return-on-investments is a challenge to infrastructure financing and liquidity. Nevertheless, it can be observed that global energy investments are increasingly shifted from fossil to renewable energy sources, e.g. by institutional investors in Norway, Germany, and the US.

From scenarios to decisions – about the right way forward

High greenhouse gas emission reductions can be achieved with a number of robust technical options. There are only few ‘hard’ guiding lines.

There is a trade-off between energy efficient pathways (BEV, FCEV) requiring novel fleets and infrastructures vs. pathways with lower energy efficiency (PtCH_4, PtL) that can be used with established propulsion systems and existing infrastructures though.

Robust sustainable development lines are options with multiple benefits (greenhouse gases, criteria pollutants, resource use, etc.), notably

- the development and deployment of more-electric propulsion systems that offer increased efficiencies and facilitate exhaust gas management;
- to step up the deployment of renewable electricity and electricity-derived fuels to drive the energy transition in transportation;
- downsizing vehicles and powertrains in terms of sufficiency and avoidance, i.e. smaller, lighter vehicles with robust combustion engine performance;
- starting with implementation timely and progressing at accelerated pace, especially in the case of systems with typically long lifetimes (the 35 years until 2050 is in fact less than one generation of aircrafts, ships, and energy infrastructure away).

Policy/regulatory

Targets are important elements for the developments in the transportation sector. Long-term targets (2050), including intermediate targets (2020, 2030, …), give orientation, guide decisions, and provide investment certainty to all actors in the transportation value chain (vehicle manufacturer, fuel supplier, distribution infrastructure provider, and not least 1st to nth tier suppliers). Currently, there is a regulatory set like the EU Renewable Fuels Directive (RED) and the EU Fuel Quality Directive (FQD) for which post-2020 targets are due to be developed for a seamless continuation and to avoid stop-and-go developments incurring additional costs.

Increasing renewable electricity demands for transport – be it directly for rail overhead lines, BEV charging, power-to-gas (PtH_2, $PtCH_4$) or power-to-liquids production (PtL) – may benefit from residual renewable electricity supplies (often called 'surpluses'). However, there are a number of other power consumers that can more easily tap residual load opportunities, e.g. power-to-heat. For a robust transport sector development and to avoid a shift of greenhouse gas emissions from the transportation sector to the power sector, a deployment of renewable power plants is needed that is in-line with electricity demand growth from the transportation sector.

Additional renewable power plant capacities to make up for transport sector electricity demands would not need to be sector exclusive. A system optimum is a pool of renewable power plants from which different electricity uses can draw from. Electricity and PtX fuel production can and should provide grid services and thus stabilise the power system. For this, grid codes are being developed among others.

To facilitate the uptake of renewable electricity in transport, existing regulatory frameworks, such as the EU Renewable Fuels Directive, the EU Fuels Quality Directive and their national implementation in Germany, the BImSchG, have to be brought forward. First steps have been taken but further steps are needed, e.g. with regard to the accountability of electricity-based fuels and the direct use of electricity in transport, including sustainability criteria to this end.

Outlook

The model and study have been developed to assess energy demand, greenhouse gas emissions and costs. Strategic implications with regard to pollutant emissions could not be analysed herein. Embedding combustion engines into increasingly electrified powertrains, however, promises to offer greater degrees of freedom for designing and operating combustion engines. Fields pending for further research to this end are thus

- Pollutant emissions from power-to-methane and power-to-liquid fuels.
- ICE design gains from a combination of synthetic fuels and combustion engines in hybridized powertrains (PHEV, REEV).

This study is based on a target scenario assuming 100% renewable electricity in transport by 2050. This methodologically 'neat' approach is reasonable for exploring the boundaries and in order to understand the principle implications attributed with this. The authors firmly believe that such target is not only achievable, in spite of its challenges, but actually necessary and worth to follow.

From a macro-economic perspective we have found that the cumulated investments seem to be manageable in principle, even for the energy-intensive and high transportation demand scenarios. The next analytical step would then be to ask, how this pathway can be taken in practical terms as renewable fuels are no fast-selling item in the foreseeable future from a micro-economic perspective. To bring energy transition in the transportation sector to the next level will require a risk-adequate investment security. International energy policies setting for robust long-term and intermediate targets with corresponding accountability could provide the necessary certainty to all actors in the fuel/vehicle value chain. What are instrumental levers and regulatory settings for successively deploying renewable fuels and (where required) alternative infrastructures? This question merits concept developments, opinion formation among industry, and debates with politics and the public.

ANNEX

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A1 TRANSPORT DEMAND SCENARIO ASSUMPTIONS

A1.1 Germany

Table 85 summarizes the scenario assumptions for the high scenario passenger transport.

- The data for the motorized individual transport for the years 2010 and 2030 are taken from VP 2030 [BVU et al 2014]. The data for 2020 are linearly interpolated. The data for 2040 and 2050 are kept constant at 2030-level, just as proposed by [MKS 2015].
- The data for public road transport for the years 2010 and 2030 are taken from VP 2030. The data for 2020 are linearly interpolated. The data for 2040 and 2050 are kept constant in accordance to the assumption of flat population development.
- The data for city rail transport (tram or subway) are neglected as their contribution to total transport energy demand is small and seen as negligible in the context of the present report. This logics follows the data in 'Verkehr in Zahlen' [VIZ 2013/14] as well as the Verkehrsprognose 2030. According to 'Verkehr aktuell' [Verkehr aktuell 2015] of German Statistics Agency in 2010 the inner city tram and subway transport demand in 2010 was 16.3 billion pkm.
- The data for rail transport (short and long distance) for 2010 and 2030 are taken from VP 2030. The data for 2020 are interpolated; the data for 2040 and 2050 are extrapolated, following the logics of [MKS 2015].
- The disaggregation of rail transport in short and long distance is based on a constant share between 2010 and 2050 of the two modes (LBST assumption). This assumption only negligibly influences the results of the study. The share for 2010 is taken from 'Verkehr in Zahlen 2013/14' [VIZ 2013/14].
- The passenger air transport demand for 2010 and 2030 is taken from VP 2030. The data for 2020 are linearly interpolated while the data for 2040 and 2050 are linearly extrapolated by LBST.

Table 85: Passenger transport demand – scenario HIGH (DE)

Billion pkm	2010	2020	2030	2040	2050
Motorized individual transport	902.4	946	991.8	991.8	991.8
Public transport					
▪ Road (short and long distance)	78.1	80.5	82.8	85.3	87.8
▪ City (tram/subway)	n.a.	n.a.	n.a.	n.a.	n.a.
▪ Rail (short and long distance)	84	92	100.1	121.5	143
– Hereof rail – short distance	47.8	52.3	57	69.1	81.4
– Hereof rail – long distance	36.1	39.7	43.1	52.4	61.6
Air total[8]	194,0	269,5	345,0	382,5	420,0
– Hereof inner Germany9	52.8	69.9	87	115.2	143.4

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions from aviation the total passenger transport demand from aviation including international aviation has been taken into account ('Air total' in Table 85).

Table 86 summarizes the scenario assumptions for the high scenario freight transport.

- The data for road transport for the years 2010 and 2030 are taken from VP 2030. The data for 2020 are linearly interpolated. The data for 2040 and 2050 are linearly extrapolated by LBST. The disaggregation into different truck classes is performed by LBST as follows.
- The data for vans and trucks smaller 3.5 t total weight is based on the number of cars and annual driving volume of 20,000 km per car. For the logics of the scenario calculations (see corresponding subchapter) this is translated into tkm based on the assumption that the average loading is 0.2 t/vehicle and a 30% of empty driving-km. These numbers are on top of the total data for road transport, as these usually do not include transport data for trucks smaller 3.5 t total weight.
- The data for trucks between 3.5 and 12 t are taken from scenario 'Mobil 2050'. There it is used for both scenarios, 'Grenzenlos' and 'Regional'. Here we use it for all scenarios.

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[8] In VP2030, p. 355 called 'Standortprinzip (Gesamtstrecke)', used in this study

[9] In VP2030, p. 355 called 'Territorial (über Deutschland)'

- The data for trucks larger 12 t and semi-trailer trucks are calculated as difference between total road transport demand and transport demand of trucks between 3.5 and 12 t.
- The data for rail transport for 2010 and 2030 are taken from VP 2030. The data for 2020 are interpolated. The data for 2040 and 2050 are linearly extrapolated by LBST.
- The data for 2010 and 2030 for inland waterways are taken from 'Verkehrsprognose 2030'. The data for 2020 are interpolated while the data for 2040 and 2050 are linearly extrapolated.
- For overseas shipping no data in terms of tkm are available. Following the logics of the national GHG inventory the GHG emissions are calculated from the bunker fuels demand. Following that logics, the fuel consumption and GHG emissions are calculated in a similar transport demand for 2010 is reverse-calculated from the assumed average heavy fuel consumption of 3 g/tkm and average ship size of 30.000 tkm. For 2020 to 2050 it is assumed that over each decade the transport demand increases by 10%.

Table 86: Freight transport demand – scenario HIGH (DE)

Billion tkm	2010	2020	2030	2040	2050
Road transport	434	522	607	728	849
▪ Trucks < 3.5 t	5.6	5.6	5.6	5.6	5.6
▪ Trucks 3.5-12 t	12	12	12	12	12
▪ Trucks > 12 t + Long trailers	422	510	595	716	837
Rail transport	107.6	130.7	153.7	186.7	219.6
Shipping					
▪ Inland waterways	62.3	69.4	76.5	85.2	92.9
▪ Overseas	900	990	1090	1200	1300

Table 87 summarizes the scenario assumptions for the low scenario passenger transport.

- The data for the motorized individual transport for the years 2010, 2020, 2030, 2040 and 2050 are directly taken from 'eMobil 2050 Regional'.
- The data for public transport are directly taken from 'eMobil 2050 Regional'. However, these data include innercity tram and subways and do not exactly match the data provided by statistics 'Verkehr in Zahlen' and 'Verkehr aktuell'. For the present context the assumptions are taken, that public road covers a constant share of 21 billion Pkm. This is almost 30% higher than the data in 'Verkehr aktuell' provided for 2010. This number is counted for public city transport until 2050. The remaining Pkm are distributed at constant share as in 2010 to short and long passenger rail transport. As

in the high scenario, the inner city transport (tram, subway) are neglected, as this does not influence the results of the present study.

- The share of public road and rail transport 2020 to 2050 is kept constant as in 2010. In the same logics, the share of short and long distance public passenger rail transport is kept constant over the whole period 2010 – 2050. Again this is attributed to the fact that each additional assumption complicates the calculations a bit further while it influences the results of the study only marginally.
- The scenario 'eMobil 2050' does not make any calculation of air transport demand. In the present context the data are taken identical to the scenario 'high'.

Table 87: Passenger transport demand – scenario LOW (DE)

Billion pkm	2010	2020	2030	2040	2050
Motorized individual transport	902.4	807	712	612	510
Public transport	183	203	222	238	249
▪ Road (short and long distance)	78.1	86.6	94.7	101.6	106.3
▪ City (tram/subway)	[21]	[21]	[21]	[21]	[21]
▪ Rail (short and long distance)	84	116.4	127.3	136.4	142.7
– Hereof rail – short distance	47.8	66.2	72.4	77.6	81.2
– Hereof rail – long distance	36.1	50.2	54.9	58.8	61.5
Air total	194,0	193,0	199,0	193,0	179,0
– Hereof inner Germany	52.8	69.9	87	115.2	143.4

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions from aviation the total passenger transport demand from aviation including international aviation has been taken into account ('Air total' in Table 87).

Table 88 summarizes the scenario assumptions for the low scenario goods transport.

- The data for road transport for the years 2010, 2020, 2030, 2040 and 2050 are taken from the scenario 'eMobil Regional'. Also the disaggregation into trucks between 3.5 to 12 tons and trucks larger 12t are taken from 'eMobil Regional'.
- The data for vans and trucks smaller 3.5 t total weight is based on the number of cars and annual driving range of 20,000 km per car. For the logics of the scenario calculations (see corresponding subchapter) this is translated into tkm based on the assumption that the average loading is 0.2 t/vehicle and 30% of empty driving-km. These numbers are on top of the total data for road transport, as these usually do not include transport data for trucks smaller 3.5 t total weight.
- The data for inland waterways are taken from scenario 'eMobil 2050 Regional'.

- The data for overseas transport demand are calculated similar to the scenario ‘high’.

Table 88: Freight transport demand – scenario LOW (DE)

Billion tkm	2010	2020	2030	2040	2050
Road transport	442	491	485	420	297
▪ Trucks < 3.5 t	5.6	5.6	5.6	5.6	5.6
▪ Trucks 3.5-12 t	12	12	12	12	12
▪ Trucks > 12 t + Long trailers	430	479	473	408	285
Rail transport	110	125	140	155	170
Shipping					
▪ Inland waterways	62	60	62	64	66
▪ Overseas	Calculated from bunker fuel demand	+10%	+10%	+10%	+10%

A1.2 EU

Table 89 summarizes the scenario assumptions for the high scenario passenger transport.

- The data for the motorized individual transport for all years are taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050’ [AEA 2012]
- The data for public road transport for all years are taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050’ [AEA 2012]
- The data for city rail transport (tram or subway) are neglected as their contribution to total transport energy demand is small and seen as negligible in the context of the present report.
- The data for rail transport (short and long distance) for all years are taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050’ [AEA 2012].
- The disaggregation of rail transport in short and long distance is based on a constant share between 2010 and 2050 of 40:60 for the two modes (LBST assumption).
- The passenger air transport demand for all years is taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050’ [AEA 2012].

Table 89: Passenger transport demand – scenario HIGH (EU)

Billion pkm	2010	2020	2030	2040	2050
Motorized individual transport	4670	5300	5720	6040	6220
Public transport					
▪ Road (short and long distance)	520	560	620	680	750
▪ City (tram/subway)	n.a.	n.a.	n.a.	n.a.	n.a.
▪ Rail (short and long distance)	430	550	640	700	700
– Hereof rail – short distance	172	220	256	280	280
– Hereof rail – long distance	258	330	384	420	420
Air total	1150	1480	1860	2200	2460
– Hereof inner EU	525	647	784	890	1004

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions from aviation the total passenger transport demand from aviation including international aviation has been taken into account (‘Air total’ in Table 89).

Table 90 summarizes the scenario assumptions for the high scenario freight transport.

- The data for road transport for all years scenario are taken from scenario bau-a from ‘EU Transport: Routes to 2050’ [AEA 2012]. The disaggregation into different truck classes is already performed within the original scenario.
- The data for rail transport for all years are taken from scenario bau-a from ’EU Transport GHG: Routes to 2050’ [AEA 2012]
- The data for inland water ways for all years are taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050.’[AEA 2012]
- The data for international shipping for all years are taken from scenario bau-a from ‘EU Transport GHG: Routes to 2050.’[AEA 2012]

Table 90: Freight transport demand – scenario HIGH (EU)

Billion tkm	2010	2020	2030	2040	2050
Road transport	1915	2255	2495	2685	2810
▪ Trucks < 3.5 t	45	45	45	45	45
▪ Trucks 3.5-12 t	170	190	220	240	250
▪ Trucks > 12 t + Long trailers	1700	2020	2230	2390	2500
Rail transport	440	530	590	590	660
Shipping	11190	14290	16650	18910	21170
▪ Inland waterways	120	140	150	160	170
▪ Overseas	11070	14150	16500	18850	21000

Table 91 summarizes the scenario assumptions for the low scenario passenger transport.

- The data for the motorized individual transport for all years are taken from scenario C5-b from ‘EU Transport GHG: Routes to 2050’ [AEA 2012]
- The data for public road transport for all years are taken from scenario C5-b from ‘EU Transport GHG: Routes to 2050’ [AEA 2012]
- The data for city rail transport (tram or subway) are neglected as their contribution to total transport energy demand is small and seen as negligible in the context of the present report.
- The data for rail transport (short and long distance) for all years are taken from scenario C5-b from ‘EU Transport GHG: Routes to 2050’ [AEA 2012].
- The disaggregation of rail transport in short and long distance is based on a constant share between 2010 and 2050 of 40:60 for the two modes (LBST assumption).
- The passenger air transport demand for all years is taken from scenario C5-b from ‘EU Transport GHG: Routes to 2050’ [AEA 2012].

Table 91: Passenger transport demand – scenario LOW (EU)

Billion pkm	**2010**	**2020**	**2030**	**2040**	**2050**
Motorized individual transport	4627	4360	4239	4216	4080
Public transport					
▪ Road (short and long distance)	545	581	665	776	879
▪ City (tram/subway)	n.a.	n.a.	n.a.	n.a.	n.a.
▪ Rail (short and long distance)	482	623	805	1048	1285
– Hereof rail – short distance	193	249	322	419	514
– Hereof rail – long distance	289	374	483	629	771
Air total	1093	881	836	1019	1273
– Hereof inner EU	525	378	333	380	452

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions from aviation the total passenger transport demand from aviation including international aviation has been taken into account ('Air total' in Table 91).

Table 92 summarizes the scenario assumptions for the low scenario freight transport.

- The data for road transport for all years are taken from scenario C5-b from 'EU Transport: Routes to 2050' [AEA 2012]. The disaggregation into different truck classes is already performed within the original scenario.
- The data for rail transport for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050' [AEA 2012]
- The data for inland water ways for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050.'[AEA 2012]
- The data for international shipping for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050.'[AEA 2012]

Table 92: Goods transport demand – scenario LOW (EU)

Billion tkm	2010	2020	2030	2040	2050
Road transport	1941	1985	2081	2135	2116
▪ Trucks < 3.5 t	61	59	65	71	74
▪ Trucks 3.5-12 t	169	182	196	209	218
▪ Trucks > 12 t + Long trailers	1710	1744	1819	1855	1824
Rail transport	440	546	648	764	893
Shipping	11153	11453	12464	14762	17056
▪ Inland waterways	123	150	182	220	264
▪ Overseas	11030	11303	12282	14542	16792

A2 VEHICLE PARAMETER ASSUMPTIONS

A2.1 Passenger

The data shown in Table 93 are derived from the following considerations.

- Motorized individual transport: The travelled passenger-kilometres are converted into car-km by the average occupation number. Though the model is prepared to vary the occupation over time, for the present context it is appropriate to keep it fixed with 1.5 persons per vehicle. This matches with the empirical data in VIZ 2013/14 when motorized cycles are not counted separately.
  Empirical data indicate annual driving volumes to be fuel-specific for gasoline and diesel powered cars with 11,300 km and 22,000 km, respectively. The car life-time varies correspondingly with about 14 years for gasoline and 9 years for diesel cars. However, in the present context – which has its focus on the switch from conventional fossil to alternative non-fossil fuels – the difference between gasoline and diesel is neglected. A 'unit car' is used with an average lifetime of 13.9 years and average driving volume of 14,000 km/a. The lifetime influences the substitution speed of elder cars to new (more efficient or alternative) cars and therefore alters the date during the intermediate status marginally. However, in the long-term, its influence is negligible. This justifies the use of a 'unit car' in favour of simplicity and model transparency.
- Public road transport is not disaggregated into city busses and long distance busses. The average occupation number is calculated from published pkm and the number of busses with 23 passengers per vehicle. This number is kept constant over the whole period. Annual average driving volume is 43,000 km/Bus
- Short distance trains. The typical train size was chosen from TR 423 and TR 430 which have 184, respectively 192 seats. Other multiple units used for short distance transport other than suburban trains typical have 120 seats. Though also larger trains (with locomotive) and smaller trains (diesel and motor coaches) exist, the typical average

size of 120 seats is chosen. According to different editions of the environmental report of DB the average utilisation of short distance trains varied over the period 2000-2005 between19.5 – 21.8%. In [IFEU 2011] the occupancy for 2009 is indicated with 23.1% based on data from Deutsche Bahn AG (DB). According to statistics from the German Federal Statistical Agency, the utilisation rate of short distance rail transport increased between 2008 and 2013 continuous from 24.1% to 26.7%, when the number of passenger-km is divided by the number of seat-km [Genesis 2015]. For the calculations a rise of the utilisation rate from 23.1% in 2010 to 30% in 2050 is assumed. In contrast, inner city tramway has a lower utilisation rate of about 19% which almost did not change over the last decade. The annual driving volume for S-Bahn Munich in 2012 was about 85,000 km/train. For the scenarios a typical driving volume of 120,000 km/yr is chosen, justified by the fact that short distance trains include regional trains with much larger activity radius that- S-Bahn. The operation time is estimated with 30 years. For the scenario calculation a share of 80% of Pkm are performed with electrical driven railcars (multiple units), 20% by diesel fuelled rail cars.

- Long distance trains. The typical vehicle size is a unit of the German ‘Intercity-Express’ (ICE) which is a high speed train similar as the French ‘train à grande vitesse’ (TGV). Actually DB operates three types of ICE (BR 403, BR 406, BR 407). Based on published statistics the average train-unit has a capacity of about 430 seats (calculation based on DB 2014]). About 70% of long distance transport is performed by ICE. The occupancy between 2000 and 2004 increased from 40.2 to 42.6%, according to various editions of DB Environmental reports. In [IFEU 2011] for 2009 the occupancy is indicated with 48.6% also based on data from the DB. For the scenario calculations occupancy of 48.6%% is chosen. The annual driving volume is estimated with 200,000 km/train. The operation train is estimated with 25 years.
- Passenger air transport. The average aircraft size at Deutsche Lufthansa between 2011 and 2013 was 170 seats. This was chosen for the calculations. The utilisation rate, according to Lufthansa, in 2013 was 82.2% [LH 2014]. For the calculations a rise of the utilisation rate from 80% in 2010 to 85% in 2050 is chosen. The annual driving volume is calculated from [LH2014] with 2.5 million km/aircraft.
The operation time is estimated with 15 years.

Table 93: Parameter setting for passenger transport modes

	Capacity [seats]	Utilisation [%] or occupation [persons/car]	Annual driving volume [km/car]	Operation time [yr]
Car		1.5 cap/car	14,000	13.9
Bus		23 cap/car	43,000	14
Train – short distance	190	25% (2010)-30% (2050)	120,000	30
Train – long-distance	430	42% (2010)-45% (2050)	200,000	25
Aircraft	170	80%(2010)-85%(2050)	2,500,000	15

These parameters are identical in all scenarios for Germany and EU-28.

A2.2 Freight

The data shown in Table 94 are derived from the following considerations.

- Trucks < 3.5 t. There exist no reliable data on the transport volume of commercial small trucks with less than 3.5 tons total weight. In many statistics they are neglected or summarized under passenger cars and vans. But as these offer the largest potential for alternative fuel strategies, they are discussed separately in these scenario calculations. These small trucks are by far the largest group with almost 2.1 million registered vehicles in Germany at end 2013 – a share of 80% of all trucks [KBA 2014]. According to [DIW 2005] in 2002 their annual driving volume was between 16,000-21,000 km. However the old classification scheme was for trucks < 3.5 t load, while the present class restriction is 3.5 t total weight. [Renewbility 2009] chose 19,489 km annual driving range for this class. For the present scenario calculations an annual driving volume of 20.000 km is chosen. In the logics of modelling, this is translated with the assumption of 30% deadload-km and 0.2 t per trip to a total transport volume of 5.6 tkm. The average operation time is chosen as 12 years, which is about 50% above the average age of the fleet (Own calculation based on statistics from [KBA 2014]).
- Trucks 3.5-12t. From [KBA 2013] follows that the total driving volume of trucks <12t in 2013 was 1.68 billion vehicle-km with about 50% usage of load capacity and about 0.46 billion deadload-kilometer. The total transport volume was about 4.47 billion tkm. From these date the average load is calculated with 2.7 t/vehicle.
  Combined with registration statistics from [KBA 2014] (334,883 vehicles between 3.5-12t) average annual driving volume is calculated with about 6,500 km/yr. Restricting the analysis on trucks between 7.5-12 t increases the driving volume to about 25,000 km/yr. [Renewbility 2009] chose the annual average driving volume for trucks between 3.5-7.5t with 22,458 km and for trucks 7.5-12t with 32,744 km. This gives a weighted average driving volume of 24,420 km, which is close to our number. The operation time is chosen with 15 years, which is about 50% above average age of the fleet.(Own calculation based on statistics from [KBA 2014]).
- Trucks >12t and trailer trucks. In 2013 the trucks >12t without trailer trucks had a driving volume of 8.21 billion vehicle km at 47% load and additional 2 billion deadload-km. With 84.4 billion tkm this results in an average load of 10.1 t for the 194,450 registered trucks. From these data the average annual driving volume is calculated with 42,700 km.
  Trailer trucks exhibited 13 billion vehicle-km with load and 3.57 billion deadload-km. From 216 billion tkm the average load of 16.7 t is calculated. The 181,998 registered trailer truck engines therefore have an average driving volume of 91,000 km/yr.
  As the fuel consumption and driving patterns of large trucks and trailer trucks are pretty close, they are combined to one group with average load of 13.5t, 10% dead-load km and average driving volume of 75,000 km/yr. The average operation time is chosen with 8 years, which derived from average age of large trucks of 6.8 years and of trailer trucks with 4.4 years. (Own calculation based on statistics from [KBA 2014]).

- Trains. From [DB 2013] the typical load per train in 2013 was 531.9 t/train, about 2% more than in 2012. For the calculations 532 t/train are chosen. As the specific energy consumption per tkm already includes deadload-km, these are not explicitly used. The annual average driving volume per train is estimated with 100,000 km/yr. The operation time with 39 years, assumed from the average age of cargo locomotives of about 26 years [Planco 2007].
- Inland barges. The average capacity of cargo barges is calculated from the number of ships, lighters and dumb barges with 1290 tons [BVB 2013/14]. From the typical return load of 13 different routes and cargo types [Planco 2007] an average return load of 60% can be calculated which is translated into 20% of empty trips (dead-load-km). The total ship driving volume with load is calculated from 17.7 billion tkm of German inland barges and the total load capacity (1290 tons) as 13.7 million ship-km. The division by the number of registered motor barges (1253 motor barges) results in the average driving volume of 10,900 km per ship. The addition of 20% empty trips gives the estimate for the total annual driving volume of 13,700 km/yr per motor barge. The average age of the fleet is about 52 years [Planco 2007]. For the calculation 60 years of average operation age of motor barges is used.
- Oversea freight vessels. The typical load capacity is 53,000 tons for oil tankers and 32,000 tons for other freight ships (own calculation with data from [RMT 2014]). For the calculation an average load of 32,000 t is assumed. The deadload-km are estimated with 40%, as by far the largest transport volume are ores (pred. iron ore) and fuels (coal and mineral oil) which have an empty-return-trip share close to 50%. The annual driving volume is estimated with 145,000 km (derived from 20 km/h average speed at 300 days, while 65 days are calculated for docking and loading/unloading). The average age of all ships in industrialized countries is about 9 years. The average age of demolished ships is close to 30 years which is chosen as typical operation time [RMT 2014].

Table 94: Parameter setting for freight transport modes

	Average load [t/vehicle-train]	Empty trip-km [%]	Annual driving volume [km/car]	Operation time [yr]
Trucks < 3.5 t	0.2	30%	20,000	12
Trucks 3.5-12 t	2.7	20%	25,000	15
Trucks > 12 t	13.5	10%	75000	10
Train	532	0%	100,000	39
Inland vessels	1,290	20%	13,700	60
Oversea freight vessels	32,000	40%	145,000	30

These parameters are identical in all scenarios for Germany and EU-28.

A3 FLEET MODELLING

A3.1 Passenger

- Passenger Car: The passenger car-km are calculated from passenger-km with a fixed car occupation of 1.5 passengers/car.
  The number of required passenger cars is calculated from total car-km. The assumed annual driving range is 14,000 km/car/yr. This driving range is kept constant for all scenarios. There is no distinction between different drive-trains or fuel-systems. The difference between last year's fleet minus abandoned cars and required cars is calculated as number of newly registered cars. This driving range is kept constant in all scenarios and for all bus driving systems. The assumed average car utilisation time is 13.9 years.
- Bus: The bus-km are calculated from passenger-km with a fixed car occupation of 23 passengers/car. The assumed annual driving range is 43,000 km/bus/yr. The assumed average bus utilisation time is 14 years.
- Regional Train: The train-km for short-distance regional trains are calculated with a fixed occupation capacity of 120 passengers/train. The utilized capacity was 23% in 2010, 24% in 2020, 26% in 2030, 28% in 2040 and 30% in 2050. The assumed annual driving range is 120,000 km/train/yr. The assumed average short-distance train utilisation time is 30 years.
- Long-distance Train: The train-km for long-distance trains are calculated with a fixed occupation capacity of 430 passengers/trans. The utilised capacity was 48.6% for all years. The assumed annual driving range is 200,000 km/train/yr. The assumed average long-distance train utilisation time is 25 years.
- Aircraft: The aircraft-km are calculated with a fixed occupation capacity of 170 seats/aircraft. The utilized capacity was 73% in 2010, 82% in 2020, 84% in 2030 and 85% in 2040 and 2050. The assumed annual driving range is 2.5 million km/aircraft. The assumed average aircraft utilisation time is 15 years.

A3.2 Freight

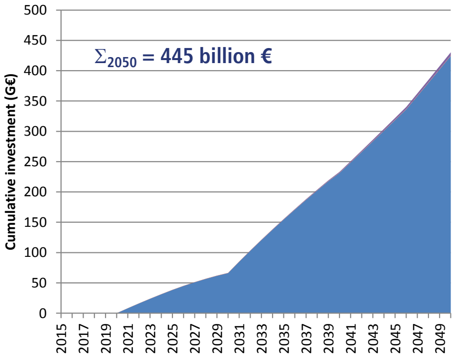
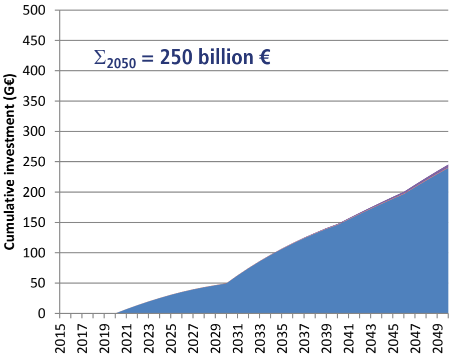
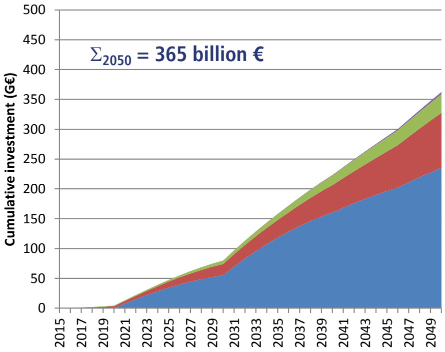
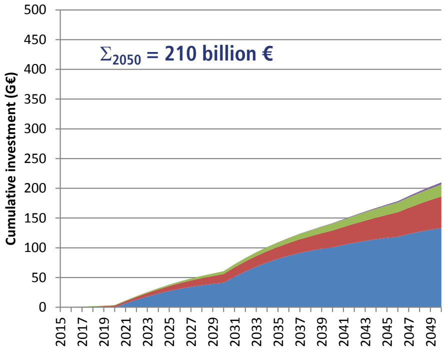
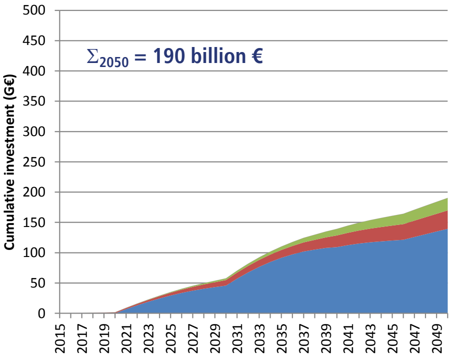
- Van<3.5 t: The vehicle-km are calculated from capacity utilisation of 0.2 t/van and 30% idle driving-km. The assumed annual driving range is 20,000 km/van/yr. The assumed average van utilisation time is 12 years.
- Truck 3.5-12t: The vehicle-km are calculated from capacity utilisation of 2.7 t/truck and 20% idle driving-km. The assumed annual driving range is 25,000 km/truck/yr. The assumed average van utilisation time is 15 years.
- Truck <12t: The vehicle-km are calculated from capacity utilisation of 13.5 t/truck and 10% idle driving-km. The assumed annual driving range is 75,000 km/truck/yr. The assumed average van utilisation time is 10 years.
- Train: The train-km are calculated from average capacity utilisation of 532 t/train. The assumed annual driving range is 100,000 km/train/yr. The assumed average train utilisation time is 39 years.
- Inland Vessel: The vessel-km are calculated from capacity utilisation of 1290 t/vessel and 20% idle shipping-km. The assumed annual shipping range is 13,700 km/vessel/yr. The assumed average vessel utilisation time is 60 years.
- Sea-Vessel: The vessel-km are calculated from capacity utilisation of 35,000 t/vessel and 40% idle shipping-km. The assumed annual shipping range is 145,000 km/vessel/yr. The assumed average vessel utilisation time is 30 years.

A4 CUMULATED INVESTMENTS PTX PLANTS

The cumulated investments into PtX plants comprise electrolysers, H_2 conditioning, CO_2 extraction, synthesis, heat management, and conditioning to final fuel. Investments for end-of-life replacements are included in the cost model. A PtX plant lifetime of 25 years is assumed. Learning curves for electrolysers are included in the cost model, too, i.e. the 1st PtX production plant is more expensive than the nth one.

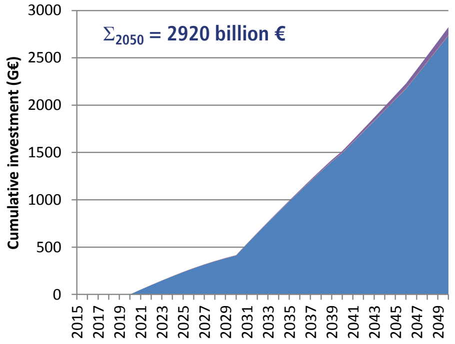
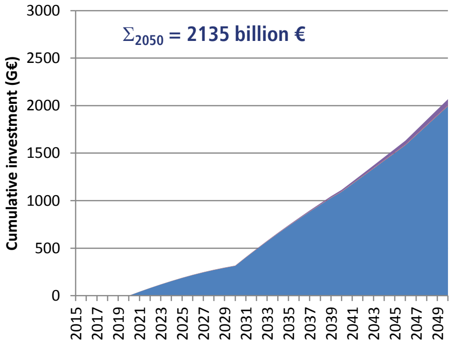
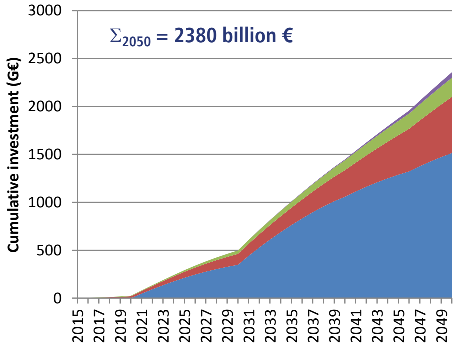
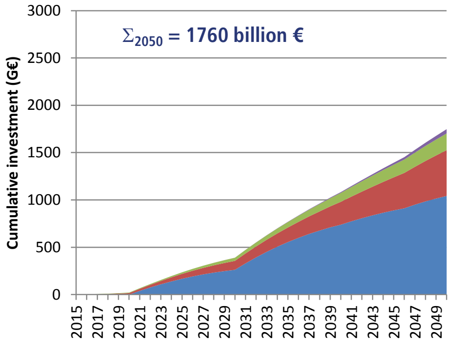
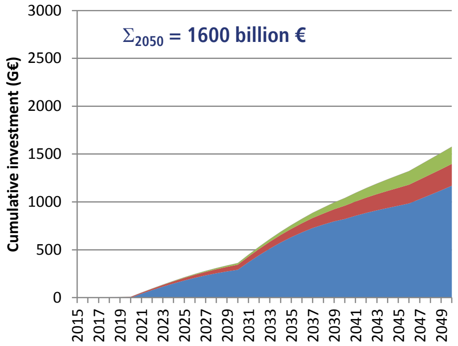
A4.1 Germany

Table 95: Cumulated investments (time-series) for PtX plants in Germany

DE	HIGH	LOW
PTL		
FVV		
eMob	Legend: 🟪 PtMethanol 🟩 PtH2 🟥 PtCH4 🟦 PtL	

A4.2 Europe

Table 96: Cumulated investments (time-series) for PtX plants in EU-28

EU-28	HIGH	LOW
PTL	 	
FVV	 	
eMob	Legend: 🟪 PtMethanol 🟩 PtH2 🟥 PtCH4 🟦 PtL	

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